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Commercial Evaluation of Tunable Hybrid Plasma (THP) System for Chlorinated Volatile Organic Compound Treatment

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Executive Summary

It has been estimated that there are 300,000-400,000 sites in the United States where soil and groundwater may be chemically contaminated. Moreover, the number of underground chemical storage tanks which are some of the additional potential sites of contamination number in the millions. The principal approaches to on-site soil remediation in use today have drawbacks of cost, complexity, secondary pollution or waste disposal issues, and public acceptance.

The integrated Tunable Hybrid Plasma (THP) approach being pursued by the Plasma Fusion Center at the Massachusetts of Technology (MIT) and by Thermo Power Corporation, a Thermo Electron Corporation, will address these issues by use of a tunable electron beam generated nonthermal plasma. The THP would be used for on-site treatment of low concentrations of volatile organic compounds (VOC) by contaminated air streams produced by vacuum extraction or in air stripping of contaminated water. It could also be used for treatment of off gases in industrial processes

Through five years of research, MIT has brought the physical basis of tunable electron beam generated plasma VOC remediation technology to a commercialization threshold, and a new generation of modular electron beam sources recently introduced to the market could significantly enhance and broaden the potential applicability of the THP. The THP approach appears to be the most energy efficient for VOC destruction. Energy cost for VOC destruction is sufficiently low that the THP technology can be cost competitive and in some cases could have significantly lower cost than other technologies, while providing an important advantage of environmentally attractive on-site treatment. Field testing, additional laboratory measurements, and design and market analyses during the coming months will facilitate our determination of commercial viability of this electron beam generated plasma technology.

Thermo Electron Corporation is already a world leader in environmental technologies, and Thermo Power brings expertise both in nonthermal plasma treatment technologies and in system integration. With a mission to bring new technologies to market, the presence of potential commercialization paths within Thermo Electron, and a

corporate structure encouraging innovation and the development of new businesses. Thermo Power is an ideally matched industrial partner for MIT.

This report projects the cost of THP operation for treatment of volatile organic compounds under a range of initial concentrations and flow rates. Using conventional, well established commercial electron beam technology, cost projections for the THP system with trichloroethylene are around 50 cents/lb. for initial concentrations in the few hundred ppm range and flow rates of 5000 cfm or greater and around $1/lb. for 1000 cfm flow rates. Cost projections for carbon tetrachloride and trichloroethane are several dollars per pound. The costs for THP treatment are generally significantly lower than costs for use of granular activated carbon and are also quite competitive with costs for thermal incineration and catalytic oxidation.

This report also discusses the potential impact of new modular electron beam technology. This technology can make possible lower cost electron beam units at low power levels. Use of these units could significantly extend the use of THP technology to low flow rate applications. The modular electron beam technology also opens up the possibility of decreasing the time required for payback on use of the electron beam equipment since it makes use of low cost, readily replaceable tubes with limited lifetime.

A number of potential environmental advantages of THP use are identified in this report. These advantages include complete on-site treatment with no requirement for transportation of contaminated material, absence of air pollution problems associated with incineration and catalytic oxidation, and potential for use over a very wide range of flow rates and contaminant concentration.

Future directions to reduce cost and extend the range of applications are discussed. These directions include the use of an imposed electric field and additives to reduce energy destruction cost, use of a totally integrated field system design, and studies of hydrocarbons and off-gas treatment.

1. THP System

1.1 Development Status

The objective of the Tunable Hybrid Plasma (THP) system developed at the MIT Plasma Fusion Center is to provide low cost, environmentally attractive treatment of dilute concentrations of volatile organic compounds (VOCs) in air streams. The system uses commercially established technologies. It contains three main components. The first component is a steady state, moderate energy electron beam which produces a low temperature plasma in the waste air stream as a destructive process. The second component is an aqueous scrubber to neutralize the byproducts. The last component is a gas analysis system with a PC-based control system which controls a feedback control loop and can be controlled remotely via a modem. This feature eliminates the need for operators during long-duration runs, reducing labor cost and allows the system to work at varying inlet concentrations with a maximum efficiency of the electron beam generator.

The initial field test of the THP field unit performed at the DOE Hanford site showed promising results of this technology for further development [1]. This technology will reach its final pre-commercialization stage after a pilot field test. This test will allow the identification of possible changes needed for industrial units and provide results which will be used to design a commercial scale unit.

At the MIT Plasma Fusion Center, several compounds have been studied with the THP laboratory device. Table 1 gives the list of these compounds. Some VOC mixtures have been studied at a very modest level. Even though the results show that THP can destroy these mixtures, understanding the destruction kinetics and the energy expense distribution requires further study.

Table 1. Compounds studied with the THP laboratory device

Compounds studied extensively	**Compounds studied at a modest level**
Carbon tetrachloride (CCl_4)	1,1,2 Trichloroethane ($C_2H_3Cl_3$)
1,1,1 Trichloroethane ($C_2H_3Cl_3$)	Freon 113 ($C_2Cl_3F_3$)
Trichloroethylene (C_2HCl_3)	Hexafluoroethane (C_2F_6)
Chloroform ($CHCl_3$)	Perfluoroethylene (C_2Cl_4)
Ethyl chloride (C_2H_5Cl)	Toluene (C_7H_8)
Vinyl chloride (C_2H_3Cl)	cis-Dichloroethene ($C_2H_2Cl_2$)
1,1 Dichloroethane ($C_2H_4Cl_2$)	

1.2 Energy Cost for VOC Destruction

Measurements with a laboratory THP device indicate that a low energy expense is possible for the destruction of a wide range of halogenated hydrocarbons [2, 3, 4]. Figure 1 gives this energy in kWhr per pound destroyed for trichloroethylene (TCE) and trichloroethane (TCA) for 90, 95, and 99% destruction removal efficiency (DRE) as a function of inlet concentration. Figure 1 also shows the electrical cost per pound of VOC destroyed assuming 7 cents/kWhr. TCE has the lowest energy expense of various compounds studied, and TCA has the highest energy expense. CCl_4 has a somewhat lower energy expense (by a factor of about two) than TCA.

Compared to plasma discharge technologies such as the silent discharge, the THP technology appears to be significantly more energy efficient [5]. The energy expense is generally five to ten times lower.

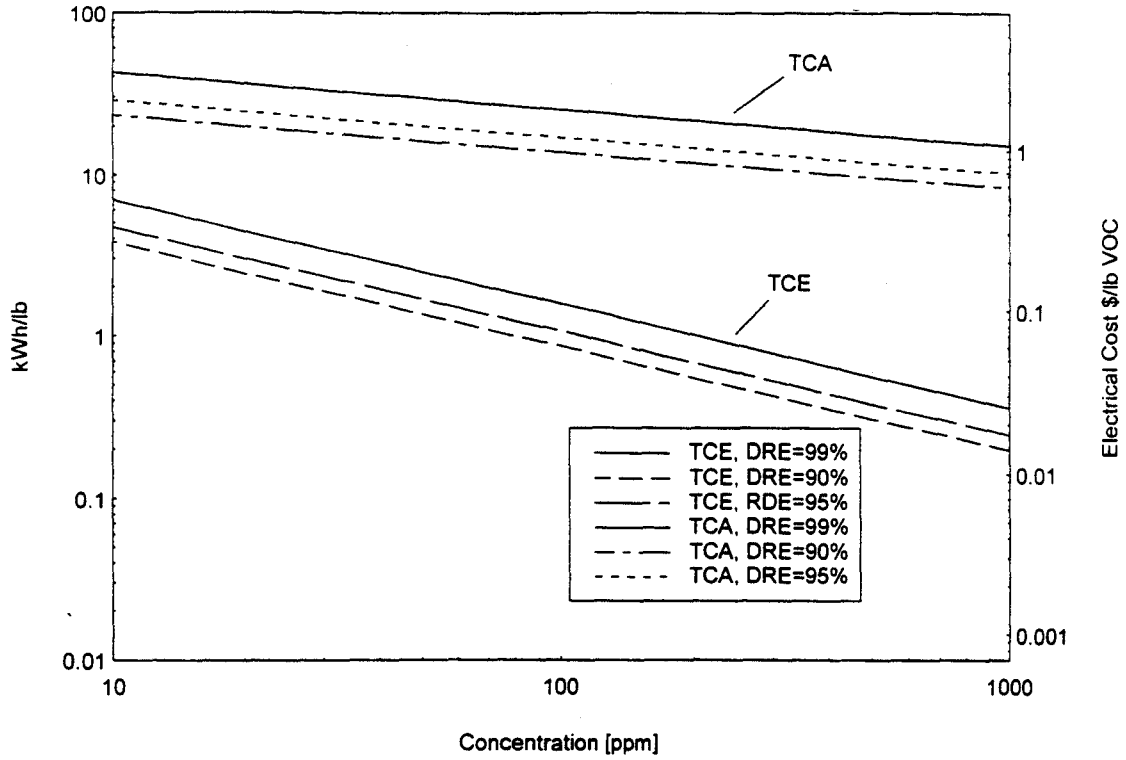


Figure 1. Energy expense and electrical cost per pound for TCE and TCA versus inlet concentration (assuming 7 cents/kWhr.)

1.3 Possibilities for Further Improvement in Efficiency

We have identified three possibilities to further reduce the energy expense for destruction of VOCs. The first is by adding an external electric field to the plasma. This approach allows the tunability of the electron energy to reach the maximum rates of the electron attachment destructive process. For TCE for example, it has been found that the energy expense can be reduced by 50% [6]. Other compounds are being investigated with the laboratory THP device.

The second possibility is by injecting additives to the plasma. This will be investigated by using the laboratory device.

The third possibility is to investigate the effect of the inlet gas stream temperature on the destruction energy expense. M.C. Hsiao et al. [7] found that the energy efficiency of plasma-assisted decomposition of diluted methylene chloride increases substantially with temperature. In an integrated system as described in section 2. 3, waste heat from coregeneration system can be used to increase the inlet gas stream temperature.

1. 4 Cost of THP Components

The key component in the present THP prototype cost estimate is the electron beam generation unit. Other components such as the scrubber (and the dryer in the case of some compounds such as CCl_4) are the same as those used with other technologies. Therefore, the potential in cost reduction for THP technology will be primarily determined by the cost of the electron beam generation unit.

1. 4. 1 Conventional Electron Beam Technology

Conventional electron beam technology using an electron beam curtain has been a well-established commercial technology for more than 20 years. The two major components are the high voltage power supply and the vacuum system which makes the vacuum in the chamber where the electrons are produced. The cost per kilowatt of the electron beam unit increases significantly at low powers and can become a major cost handicap for small electron beam systems (less than a few kWatts).

1. 4. 2 Modular Electron-Beam Technology

A recent electron-beam technology developed by AIT, Inc., Torrance, California, uses modular vacuum sealed tubes. This new technology eliminates the need for a vacuum system. It allows versatility in the use of modular electron beam tubes and can

considerably reduce the capital cost of an electron beam system for use in applications with low flow rates and concentrations. Use of this technology could also facilitate applications where it is not desired to have a long capital equipment payback time; the tubes are projected to have a low capital cost along with a limited lifetime.

This technology uses an electron beam accelerator in the range of 30-75 kV and eliminates the need of a heavy lead shielding. Each tube has a window of 2x25 mm and produces around 150 W. These parameters can be customized for a specific use. Large scale production of the electron beam tubes is projected to start around May 1996 [8]. These tubes have an efficiency of 80% for conversion of electricity to beam power and a projected lifetime of 2000 to 3000 hours [8].

The need of a versatile, non-expensive and modular electron beam technology for a very wide range of applications appears to be significantly important that its cost will drop as a result of mass production. Possible applications are: surface treatment, ink drying, textiles treatment, and sterilization, in addition to waste stream treatment.

The building of a THP system using modular technology would consist of locating a number of electron beam tubes around a flow channel. The number of electron beam tubes will be determined by the air stream flow rate, nature of the VOC, and the concentration. A schematic of a system using this technology is given in Figure 2.

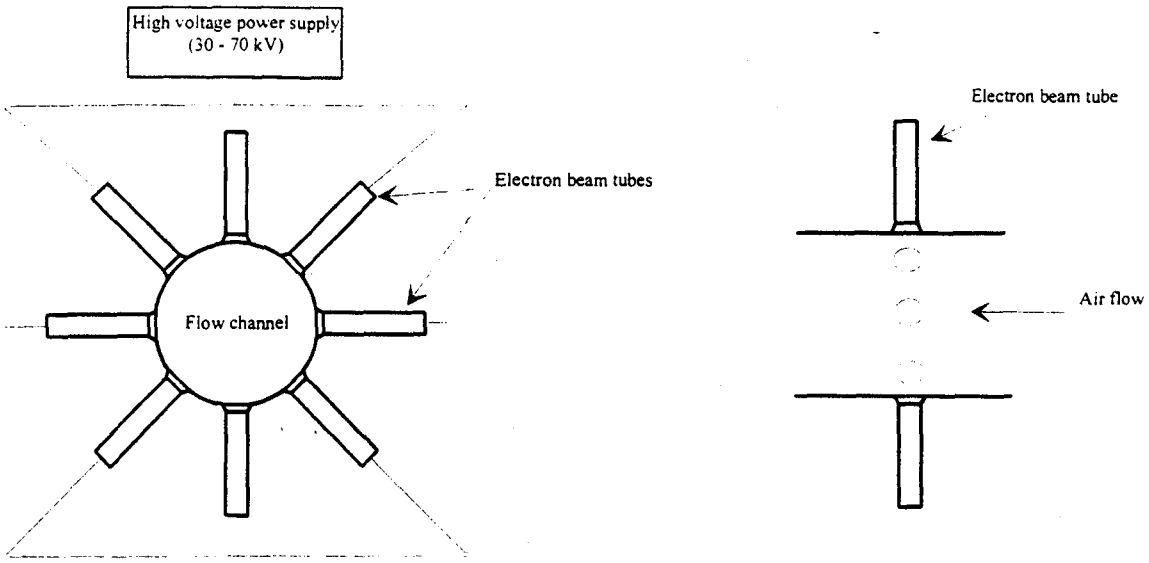


Figure 2. Electron beam generator using modular electron beam tubes

1. 4. 3 Comparison of Conventional and Modular Electron Beam Systems

Conventional electron beam technology in the range of 150 - 300 keV is a well known technology and has been on use for more than 20 years. Power output of conventional electron bem systems can be customized for a given application and can reach several hundred kilowatts. The electron beam window transparency is 70 to 80% and the beam can penetrate 10 to 30 cm in air.

The modular electron beam is a new promessing technology in the range of 30 to 75 kV. The maximum power per tube is about 100 - 200 watts which makes it very attractive for applications where low power electron beam systems are needed. The electron beam window transparency can reach 95%. The following table summerizes the comparison of modular and conventional electron beam technologies.

	Conventional	Modular
Voltage acceleration range [kV]	150 - 300	30 - 50
Maximum power [Watts]	Several hundred kW	100 - 200 per tube
Linear current density [mA/cm]	0.6	0.8
Electron Beam transparency	70 - 80%	up to 95%
Window Size [mm]	customized	2 x 25
Window Lifetime in air [hours]	> 5000	2000 - 3000
Penetration in air [cm]	~15 cm @ 175 kV	~2 cm

1. 4. 4 Control System

The control system used in the initial field tests consisted of a gas analyzer (Fourier Transform Infrared spectrometer (FTIR) or an Opto-acoustic analyzer) and a PC-based control system for data acquisition and control. For commercial THP systems, the gas analyzer and the data acquisition system can be made much simpler and customized for the VOC that is to be treated. This approach will reduce the overall control cost.

2. Comparison of THP to Other VOC Treatment Technologies

2. 1 THP Cost Estimates

Estimation of the THP electron beam component cost has been made on the basis of the conventional electron beam technology. An efficiency of 80% for the conversion of the electricity to electron beam power is assumed. The cost of an electron beam generator with the conventional technology is about $5/Watt for systems with powers higher than 60 kW [9]. This cost can be reduced to 3 to 4$/Watt for mass production and high power systems. However, as the power goes down, the cost of the electron beam

system increases. The cost per kilowatt is taken as a function of the electron beam system power. It is estimated to be $20/W for a 1 kW power system, and $5/W for a 60 kW system.

Based on discussions with AIT Inc., the cost of the electron beam tubes for the modular technology is currently at $20/Watt and will eventually be at $1/Watt [8]. Cost of the power supply is about $1/Watt. The total electron beam cost for the modular technology will be around $2/Watt over the lifetime of the tube.

2. 2 Cost Comparison

A comparison has been made with present technologies which are in direct competition with the THP technology. These technologies are: granular activated carbon (GAC) adsorption, incineration, and thermal catalytic oxidation. Each of these methods has certain advantages and disadvantages over a range of different parameters. These parameters include the type of VOC, concentration, and flow rate.

The cost comparison takes into account the destruction of the VOC and the scrubbing of the final byproducts. The cost of the scrubber is expected to be the same for the same flow rates.

The total cost takes into account the capital cost with an amortization over 10 years with an interest rate of 10% per year, the operating cost, and the maintenance cost. It is calculated for 90% availability of the different systems. Costs in reference [10] are given in 1988 dollars. In order to actualize these costs to 1995 dollars, a 5% per year multiplier is assumed. For THP systems, a 2.5 standard industrial multiplier index is assumed to cover the research and development costs, marketing costs, and a profit margin.

The cost estimate for thermal incineration, catalytic oxidation, and granular activated carbon are calculated from Reference [10]. The cost estimate for thermal incineration is calculated for 75% heat recovery. It is calculated for 50% heat recovery, and 95% destruction efficiency for catalytic oxidation.

For THP technology the operating cost is assumed to be negligible since this system is designed to run automatically and be self-controlled. The maintenance cost takes into account change of the scrubber solution and routine checks of the system by a qualified person. A certain amount of money is assumed for parts.

For all these technologies, we assume VOC concentrations of 25, 50, 100, 200, and 500 ppm and flow rates of 100, 500, 2500, 5000, and 10000 cfm. All the results are given for 95% destruction efficiency (DRE).

Because of a lack of information on kinetics of the decomposition of mixtures with the THP, the cost comparison is made for three different compounds TCE, TCA, and CCl_4 but not for mixtures.

Tables 2, 3, 4, and 5 give examples of the parameters used to calculate costs for the different technologies. They are given for TCE with two typical flow rates (1000 and 5000 cfm) and four different concentrations. The cost per pound of VOC destroyed is calculated by dividing the total cost per year over the amount of VOC processed per year. The total cost per year is the sum of the capital cost amortized over 10 years and the total operating cost (maintenance and operating). The capital cost is obtained by multiplying the equipment cost by a standard industrial profit index of 2.5 and by an interest index of 2 (10% over 10 years). Table 2 uses the energy expense per molecule of TCE destroyed to calculate the power needed for each combination of flow rate and concentration. The electron beam energy efficiency is assumed to be 80% of the wall plug power.

E-Beam Cost $/Kw	Variable		THP Technology Chart Calculation						
Standard Industrial Index	2.5								
Interest Index 10%/year	2								
VOC	TCE								
Molecular Weight g/mole	131.39								
Concentration [ppm]	50	100	200	500		50	100	200	500
Flow Rate [cfm]	1000	1000	1000	1000		5000	5000	5000	5000
Destruction Efficiency	0.95	0.95	0.95	0.95		0.95	0.95	0.95	0.95
Energy Expense [eV/molecule]	18.28457	11.73345	7.529505	4.188754		18.28457	11.73345	7.529505	4.188754
Dose [kJ/kg]	2.986511	3.832965	4.919327	6.841701		2.986511	3.832965	4.919327	6.841701
Dose [kWh/kgVOC]	3.764976	2.416034	1.5504	0.862506		3.764976	2.416034	1.5504	0.862506
Power needed [kW] (80% efficiency)	2.11445	2.713739	3.482883	4.843924		10.57225	13.5687	17.41442	24.21962
VOC Processed kg/year	3977.719	7955.439	15910.88	39777.19		19888.6	39777.19	79554.39	198886
Salt Produced kg/year (NaCl)	4813.588	9627.177	19254.35	48135.88		24067.94	48135.88	96271.77	240679.4
E-Beam Cost $	26932.76	30500.81	35067.57	43114.13		76499.23	93655.57	115368.4	152956.7
Scrubber Cost $	2500	2500	2500	2500		10000	10000	10000	10000
Control Cost $	10000	10000	10000	10000		13000	13000	13000	13000
Miscellaneous	8000	8000	8000	8000		10000	10000	10000	10000
Dryer Cost $									
Total Equipment Cost $	47432.76	51000.81	55567.57	63614.13		109499.2	126655.6	148368.4	185956.7
Total Capital Cost $	237163.8	255004.1	277837.9	318070.6		547496.2	633277.8	741842	929783.7
Total Capital Cost $/year over 10yrs	23716.38	25500.41	27783.79	31807.06		54749.62	63327.78	74184.2	92978.37
NaOH $/year	1089.869	2179.738	4359.476	10898.69		5449.345	10898.69	21797.38	54493.45
Maintenance $/year	5200	5200	5200	5200		7600	7600	7600	7600
E-B Elect. Cost $/year	1166.922	1497.658	1922.134	2673.265		5834.612	7488.292	9610.668	13366.32
Other Elect. Cost $/year	116.6922	149.7658	192.2134	267.3265		583.4612	748.8292	961.0668	1336.632
Total Operating Cost $/year	7573.484	9027.163	11673.82	19039.28		19467.42	26735.81	39969.12	76796.41
Total Cost $/year (10 yrs Amortization)	31289.86	34527.57	39457.61	50846.35		74217.04	90063.6	114153.3	169774.8
Tot. Cost $/lb VOC (10 yrs Amortization)	3.57	1.97	1.13	0.58		1.694163	1.027948	0.651449	0.387547

Table 2. Electron beam calculation chart

Annual Rates	0.05		Thermal Incineration Chart Calculation						
Interest Index 10%/year	2								
TCE (g/mole)	131.39								
TCA (g/mole)	133.4								
CCl4 (g/mole)	153.82								
Concentration [ppm]	50	100	200	500		50	100	200	500
Flow Rate [cfm]	1000	1000	1000	1000		5000	5000	5000	5000
Incinerator Cost 70% HR	344253.1	344253.1	344253.1	344253.1		499424.3	499424.3	499424.3	499424.3
Scrubber Cost $	2500	2500	2500	2500		5000	5000	5000	5000
Total Capital Cost $ 70% HR	693506.2	693506.2	693506.2	693506.2		1008849	1008849	1008849	1008849
Total Capital Cost $/year over 10yrs	69350.62	69350.62	69350.62	69350.62		100884.9	100884.9	100884.9	100884.9
Methane cfm 70% HR	15.62413	15.62413	15.62413	15.62413		78.12067	78.12067	78.12067	78.12067
Methane Cost $/year 70% HR	33923.96	33923.96	33923.96	33923.96		169619.8	169619.8	169619.8	169619.8
NaOH $/year TCE	980.8822	1961.764	3923.529	9808.822		4904.411	9808.822	19617.64	49044.11
NaOH $/year TCA	980.8822	1961.764	3923.529	9808.822		4904.411	9808.822	19617.64	49044.11
NaOH $/year CCl4	1307.843	2615.686	5231.372	13078.43		6539.214	13078.43	26156.86	65392.14
Maintenance (Scrubber) $/year	2080	2080	2080	2080		4160	4160	4160	4160
Elect. Cost $/year	4137.386	4137.386	4137.386	4137.386		20686.93	20686.93	20686.93	20686.93
Labor Cost $/year	11333.25	11333.25	11333.25	11333.25		11333.25	11333.25	11333.25	11333.25
Maintenance Cost $/year	28333.13	28333.13	28333.13	28333.13		28333.13	28333.13	28333.13	28333.13
Total Operating Cost $/year 70% HR	80788.6	81769.48	83731.25	89616.54		239037.5	243941.9	253750.7	283177.2
Total Cost $/year 70% HR over 10yrs	150139.2	151120.1	153081.9	158967.2		340922.4	345826.8	355635.6	385062.1
VOC Processed kg/year TCE	3579.947	7159.895	14319.79	35799.47		17899.74	35799.47	71598.95	178997.4
VOC Processed kg/year TCA	3634.713	7269.427	14538.85	36347.13		18173.57	36347.13	72694.27	181735.7
VOC Processed kg/year CCl4	4191.092	8382.183	16764.37	41910.92		20955.46	41910.92	83821.83	209554.6
Cost $/lb TCE 70% HR	19.04028	9.582337	4.853365	2.015982		8.646985	4.385689	2.255041	0.976652
Cost $/lb TCA 70% HR	18.75339	9.437955	4.780237	1.985606		8.516697	4.319608	2.221063	0.961937
Cost $/lb CCl4 70% HR	16.29925	8.220461	4.181066	1.75743		7.421501	3.781587	1.961629	0.869655

Table 3. Thermal incineration calculation chart

Combustion Temperature F	1000		Catalytic Incineration Chart Calculation						
Annual Rates	0.05								
Interest Index	2								
TCE (g/mole)	131.39								
TCA (g/mole)	133.4								
CCl4 (g/mole)	153.82								
Concentration [ppm]	50	100	200	500		50	100	200	500
Flow Rate [cfm]	1000	1000	1000	1000		5000	5000	5000	5000
Incinerator Cost 50% HR	183041.9	183041.9	183041.9	183041.9		398725.8	398725.8	398725.8	398725.8
Scrubber Cost $	2500	2500	2500	2500		5000	5000	5000	5000
Total Capital Cost $ 50% HR	687139.6	687139.6	687139.6	687139.6		1474351	1474351	1474351	1474351
Total Capital Cost/year $/year 50% HR	68713.96	68713.96	68713.96	68713.96		147435.1	147435.1	147435.1	147435.1
Catalyst Bed Requirement ft3 50% HR	1	1	1	1		10.08926	10.08926	10.08926	10.08926
Methane cfm 50% HR	8.926042	8.926042	8.926042	8.926042		44.63021	44.63021	44.63021	44.63021
Catalyst Cost $/year 50% HR	1815.03	1815.03	1815.03	1815.03		18312.31	18312.31	18312.31	18312.31
Catalyst Cost $/year 0% HR	5185.8	5185.8	5185.8	5185.8		52973.91	52973.91	52973.91	52973.91
Methane Cost $/year 50% HR	15073.88	15073.88	15073.88	15073.88		75369.39	75369.39	75369.39	75369.39
NaOH $/year for TCE	980.8822	1961.764	3923.529	9808.822		4904.411	9808.822	19617.64	49044.11
NaOH $/year for TCA	980.8822	1961.764	3923.529	9808.822		4904.411	9808.822	19617.64	49044.11
NaOH $/year for CCl4	1307.843	2615.686	5231.372	13078.43		6539.214	13078.43	26156.86	65392.14
Maintenance (scrubber) $/year	5200	5200	5200	5200		7600	7600	7600	7600
Elect. Cost $/year	2192.053	2192.053	2192.053	2192.053		10960.27	10960.27	10960.27	10960.27
Labor Cost $/year	11333.25	11333.25	11333.25	11333.25		11333.25	11333.25	11333.25	11333.25
Maintenance Cost $/year	53333.13	53333.13	53333.13	53333.13		53333.13	53333.13	53333.13	53333.13
Total Operating Cost $/year 50% HR	89928.22	90909.1	92870.87	98756.16		181812.8	186717.2	196526	225952.5
Total Cost $/year (10 yrs Amortization) 50% HR	158642.2	159623.1	161584.8	167470.1		329247.9	334152.3	343961.1	373387.6
Total Cost $/year (10 yrs Amortization) 0% HR	147170.4	148151.2	150113	155998.3		391493.2	396397.7	406206.5	435632.9
VOC Processed kg/year TCE	3579.947	7159.895	14319.79	35799.47		17899.74	35799.47	71598.95	178997.4
VOC Processed kg/year TCA	3634.713	7269.427	14538.85	36347.13		18173.57	36347.13	72694.27	181735.7
VOC Processed kg/year CCl4	4191.092	8382.183	16764.37	41910.92		20955.46	41910.92	83821.83	209554.6
Tot. Cost $/lb VOC 50% HR TCE	20.11861	10.1215	5.122946	2.123814		8.350879	4.237636	2.181014	0.947042
Tot. Cost $/lb VOC 50% HR TCA	19.81547	9.968994	5.045756	2.091814		8.225052	4.173786	2.148152	0.932772
Tot. Cost $/lb VOC 50% HR CCl4	17.8493	8.977776	4.542015	1.880559		7.214036	3.660145	1.8832	0.817032

Table 4. Catalytic oxidation calculation chart

VOC	TCE		GAC Chart Calculation						
Annual index	0.05								
Interest Index	2								
VOC Molecular Weight g	131.39								
Adsorption Efficiency	0.165855	0.185436	0.207329	0.240286		0.165855	0.185436	0.207329	0.240286
CAG Cost $/lb	2								
Flow Rate cfm	1000	1000	1000	1000		5000	5000	5000	5000
Concentration ppm	50	100	200	500		50	100	200	500
Total VOC Processed lb/year	7885.347	15770.69	31541.39	78853.47		39426.73	78853.47	157706.9	394267.3
Carbon Requirement lbs	241.2154	431.4885	771.8509	1664.965		1206.077	2157.443	3859.254	8324.824
Number of Canisters	1.608103	2	5.145673	11.09977		8.040514	14.38295	25.72836	55.49883
Carbon Requirement lbs/year	52826.18	94495.98	169035.3	364627.3		264130.9	472479.9	845176.7	1823137
Carbon Cost	105652.4	188992	338070.7	729254.6		528261.8	944959.8	1690353	3646273
Canister Cost $	1570.312	1953	5024.749	10838.92		7851.562	14044.95	25123.75	54194.61
Equipment Cost $	1884.375	2343.6	6029.699	13006.71		9421.874	16853.94	30148.5	65033.53
Control System	13000	13000	13000	13000		13000	13000	13000	13000
Total Capital Cost $/year	211995.6	378843.3	678352.3	1463278		1059978	1896099	3391761	7316392
Waste Disposal	141.111	175.5	451.5328	974.0044		705.5551	1262.104	2257.664	4870.022
Cost $/lb VOC	26.90265	24.03311	21.52105	18.56928		26.90265	24.06187	21.52105	18.56928

Table 5. GAC calculation chart

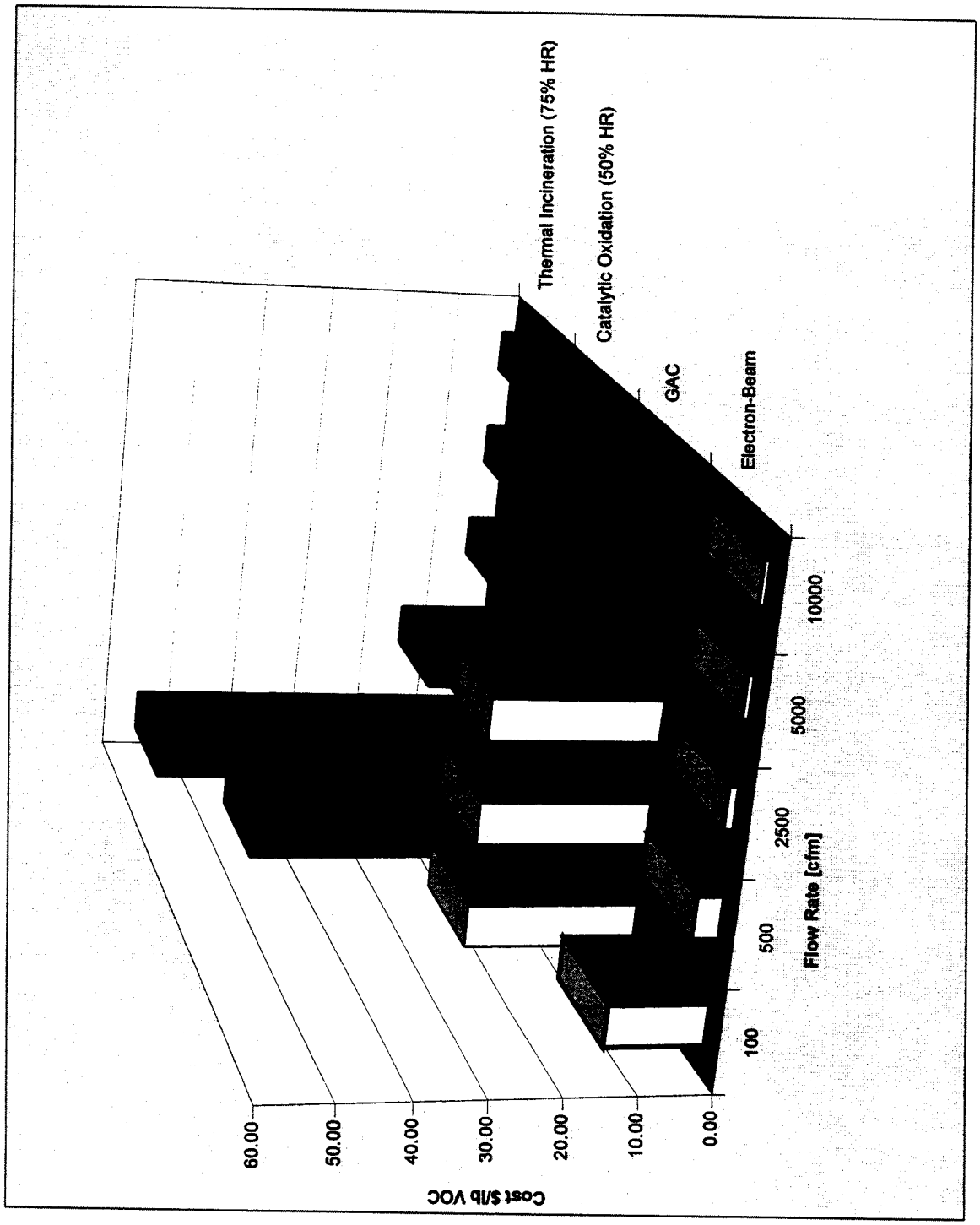
Figures 3, 4, and 5 give cost comparisons for 95% destruction of 100 ppm TCE, TCA, and CCl_4 versus flow rate, using thermal incineration, GAC, and THP technology. Cost comparison for other concentrations (25, 50, 200, 500 ppm) are given in Appendix A. Destruction cost for TCE, TCA, and CCl_4 are given in Table 6 for the different technologies for a typical concentration of 200 ppm and typical flow rate of 1000 and 5000 cfm.

Table 6. Estimated treatment costs for TCE, TCA, and CCl_4 with 200 ppm initial concentration and DRE of 95% at 1000 and 5000 cfm (in $/lb of VOC destroyed)

	TCE		**TCA**		**CCl_4**	
Flow rate [cfm]	**1000**	**5000**	**1000**	**5000**	**1000**	**5000**
THP	1.13	0.65	7.54	4.61	3.60	2.62
Thermal incineration	4.85	2.26	4.78	2.22	4.18	1.96
Catalytic oxidation	4.23	2.00	4.17	1.97	3.86	1.75
GAC	21.52	21.52	21.2	21.2	24.79	24.79

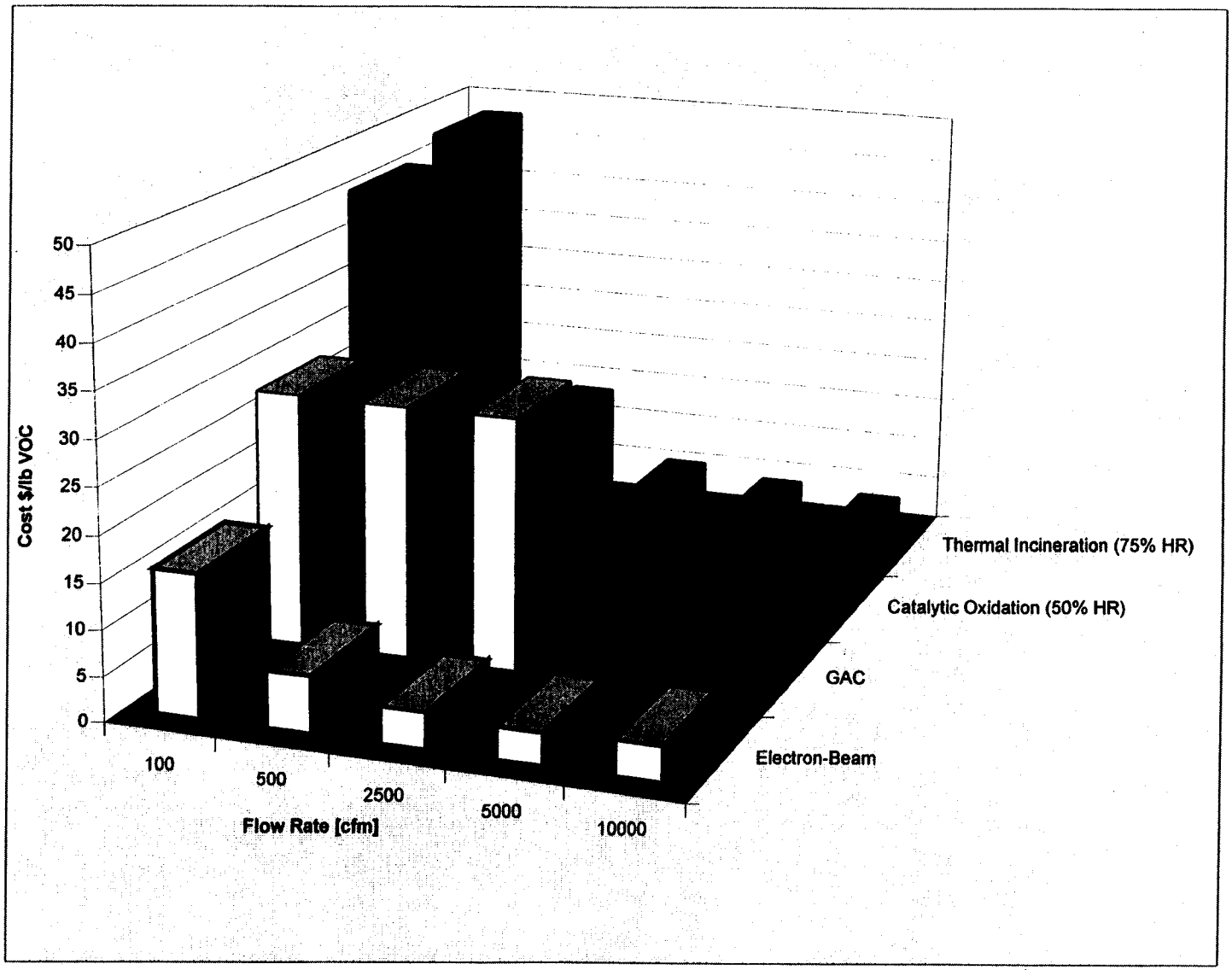
Compare Chart 26

Figure 3. Cost Estimate for Destruction of 100 ppm TCE



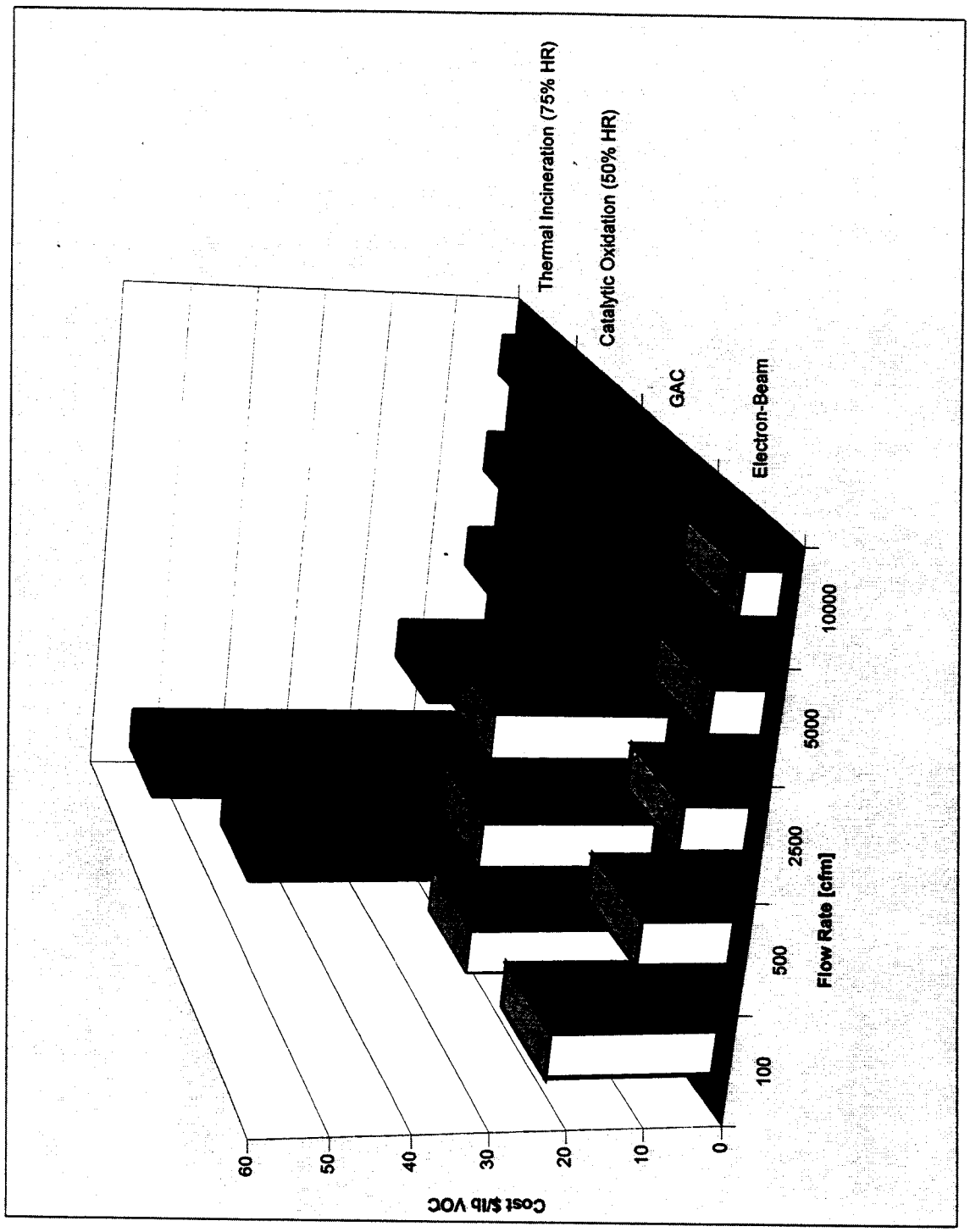
Compare Chart 30

Figure 4. Cost Estimate for Destruction of 100 ppm CCl_4



Compare Chart 36

Figure 5. Cost Estimate for Destruction of 100 ppm TCA



2. 3 Possibilities for Cost reduction for THP System

Present commercial pump-and-treat remediation methods for VOC-contaminated soils require complex installations of interconnected equipment, each sub-unit typically in its own mobile trailer. The complete remediation system may be comprised of: a pumping facility to draw VOCs from the soil, a treatment facility, a chemical scrubber, and, at many sites, a diesel electric generator to provide power for pumps, controls, and VOC processing. To operate effectively, this array of equipment requires close coordination among subcontractors and equipment manufacturers, boosting labor and material costs. The complexity of the installation increases the likelihood of equipment failure and physically clutters the remediation site, and the electric generating equipment and/or remediation unit may itself produce significant secondary pollution and acoustic noise.

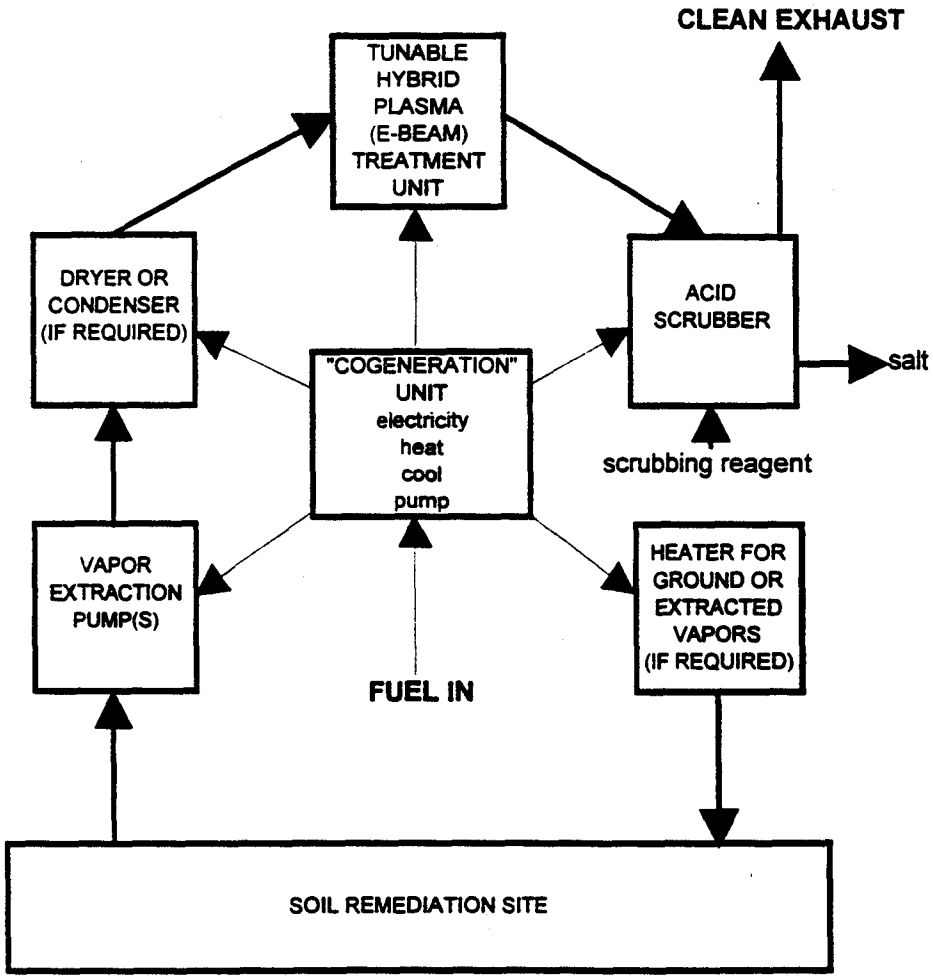
We are investigating the application of Tecogen's expertise as a designer and manufacturer of electric cogeneration equipment and associated control systems, to the design of a fully integrated unit for VOC remediation of soils using the Tunable Hybrid Plasma technique. Tecogen's CM-60 cogeneration module operating on propane fuel, for example, could (conservatively) provide all of the electric, thermal, and pumping power requirements for a 1000 cfm throughput, 200 ppm VOC remediation system. Measuring 82"x42"x46," a customized version of the indoor configuration of this fully automated, low pollution cogeneration module could serve as the complete utility provider for a single trailer integrated remediation unit.

This system integration concept is represented schematically in Figure 6. In addition to vacuum pumping, it may be desirable to employ waste heat or electricity from the cogeneration unit to enhance vapor extraction efficiency from the soil being treated. For some VOCs, a dryer may also be used on the extracted gas stream (example: for carbon tetrachloride remediation) to improve the efficiency of the THP process.

Figure 6

FULLY INTEGRATED PUMP-AND-TREAT SYSTEM CONCEPT FOR ECONOMICAL VOC REMEDIATION

NATURAL GAS OR PROPANE IN - - - - - - - - CLEAN AIR OUT



Regeneration of the dryer could also use heat from the cogeneration unit. The waste heat could be used to increase the inlet gas stream temperature in order to lower the destruction energy expense of VOCS [7]. The THP processing unit itself will be powered by the cogenerator's electric output, as will all electronic equipment and controls. The water in the salt solution remaining after chemical scrubbing may be evaporated or recycled, again using waste heat.

The economies and reliability which could be realized from such an integrated remediation device would complement the lower VOC processing costs associated with the THP technology. Thermo Remediation, a Thermo Electron company and world leader in soil remediation, has found that site scheduling difficulties and inefficient equipment utilization could negatively impact the profitability of on-site soil remediation enterprises. Future commercialization studies would address both the direct operating cost of an integrated VOC remediation system, and the indirect costs associated with equipment utilization, as enhanced by an integrated design.

2. 4. Overall Comparisons

2. 4. 1 Granular Activated Carbon Adsorption

Adsorption is a surface phenomenon where volatile organic compounds are selectively adsorbed on the surface of such materials as activated carbon. A carbon adsorption system may have difficulties when controlling an emission stream containing certain compounds such as acetone[10]. This compound can exothermically polymerize on the carbon bed, clogging the pores on the surface of the carbon which reduces its efficiency.

Granular activated carbon is used mainly in two different systems:

(a) Fixed bed regenerative systems: This method is used to control continuous VOC emissions with flow rates ranging from 2000 cfm to over 200,000 cfm with a wide range of VOC concentration (few ppm to 10,000 ppm).
(b) Carbon canister systems: This method is used for control of intermittent lower volume air streams (less than 2000 cfm) with relatively moderate concentrations. High flow rates and high concentrations require the use of a very large amount of carbon.

The cost of carbon adsorption can vary greatly depending primarily on regulatory requirements and regeneration costs. Typical overall costs quoted range from $10 to $75/kg of VOC, with the lower costs associated with moderate concentrations (a few hundred ppm, depending on the VOC), flow rates less than 2,000 cfm, and on-site regeneration [11].

Advantages of GAC are:

- Simple technology
- On-site incineration can be avoided

Disadvantages are:

- Relatively high costs for high flow rates when using carbon canister systems
- Risk of fire resulting from oxidation reactions stimulated by the heat of adsorption
- Adsorption efficiency very dependent on the temperature, nature of VOC adsorbed, and stream humidity
- Required disposal of unregenerable carbon that may be subject to land disposal restrictions
- Shipping and handling problems associated with regenerating the GAC for carbon canister systems

- Without regeneration, it is a transfer of the VOC from one phase to another
- 3 to 5% of VOC adsorbed on virgin activated carbon is adsorbed so strongly that it cannot be desorbed during regeneration, reducing the adsorption capacity for additional cycles
- Limited regeneration lifetime (typically 5-10 cycles), so that ultimately one must dispose of unregenerable carbon that may be subject to landfill restrictions
- Problems of desorption may occur with varying inlet concentration sources

2. 4. 2 Thermal Incineration

Thermal incineration is a simple technology where VOCs are oxidized at high temperature (~900 C) and is suitable for high flow rates (>10,000 cfm) with high concentrations (> a few hundred ppm). Due to the low energy value of most chlorinated VOCs, this technology requires an auxiliary fuel source that will also increase the emission of carbon dioxide. Total costs for incineration are approximately $2-$6/kg of VOC [11].

Advantages of incineration are :

- High destruction efficiency (99.9%) can be reached
- Simplicity of the technology
- Relatively low cost for high flow rates and high concentrations

Disadvantages are:

- Possible lack of public acceptance
- Production of undesirable combustion products
- High cost for low concentrations and low flow rates

- Flame inhibition properties of chlorinated compounds can lower the destruction efficiency

2. 4. 3 Thermal Catalytic Oxidation

This method uses a catalyst to lower the energy needed for VOC oxidation. It operates at approximately 500 C (versus 900 C for incineration). This technology is suitable for moderate flow rates and concentrations. It becomes energy-intensive as the VOC concentrations drop below 100 ppm. The typical destruction efficiency of this technique is about 95%. Greater destruction efficiency (99%) can be achieved by using greater catalyst volumes and/or higher temperatures. However, operation in this regime can make thermal catalytic oxidation uneconomical [10].

Advantages of thermal catalytic oxidation:

- Relatively low temperature operation
- Relatively low cost

Disadvantages of thermal catalytic oxidation:

- Possible lack of public acceptance
- Catalyst attrition
- Possible emission of heavy metals from the catalyst such as chromium
- Poisoning of the catalyst and need of its regeneration
- Problem of non-regenerable catalyst disposal
- Limited destruction efficiency (95%) for an economically acceptable destruction cost
- Destruction efficiency very dependent upon catalyst temperature. This makes this technology not suitable for streams with varying inlet VOC concentrations, a situation which is encountered in most vapor extraction and VOCs air stripping sites

2. 4. 4 Tunable Hybrid Plasma Technology

The THP technology uses an electron beam generated plasma to destroy VOCs. The destruction mechanism for chlorinated VOCs is a dissociative electron attachment [2]. In addition to that, the double-bond (non-saturated) compounds such as ethenes (TCE, PCE) are destroyed by a chlorine chain reaction [4]. This technology can be suitable for low (10 to ~ 200 ppm) concentrations and high flow rates (a few cfm to a few thousand cfm).

Potential advantages of the THP technology include:

- Relatively low cost on-site destruction at varying concentrations
- Elimination of undesirable products of combustion
- Capability for complete (>99.9%) on-site destruction of volatile organic compounds
- Capability of tunability for desired level of destruction
- High throughput
- Versatility
- No need for regenerables such as a catalyst or granular activated carbon
- Possibility of building very small systems for very low flow rates with modular electron beam technology
- Attractive environmental and public acceptability features

Disadvantages of Electron-Beam Tunable Hybrid Plasma Technology:

- High availability low cost operation of commercial-scale system not yet demonstrated
- Application to full range of compounds not been demonstrated

3. Promising Niche for THP Systems

On the basis of the comparisons between THP systems and competitive technologies, it appears that the niche for the THP technology can be found for:
- flow rates from a few cfm up to a few thousand cfm
- VOC concentration from a few ppm up to a few hundred ppm, depending on the VOC processed.

For the purpose of cost comparison between the different technologies presented in this report, we define a "Cost ratio, C_r", as the ratio of the cost/pound of VOC processed by technologies such as thermal incineration, catalytic oxidation, and GAC over the cost/pound of VOC processed by THP technology. For TCE, the cost for thermal incineration relative to THP is highest for low concentrations and moderate flow rates as shown in figure 7. However, for TCA the cost ratio is highest for low concentrations and low flow rates as shown in figure 8. The cost ratio is expected to be comparable for all the ethenes because of the similarity of their reaction mechanism with the TCE one.

Figure 9 throught figure 15 give different cost ratios between the THP system on one hand and thermal incineration, catalytic oxidation, and GAC on the other hand for TCE, TCA, and CCl_4.

It appears from this study that THP technology has potentially very attractive features, environmental attractiveness and cost effectiveness over a wide range of concentrations, flow rates, and VOCs. This range can be calculated for each compound or mixture.

Ratio Chart 53

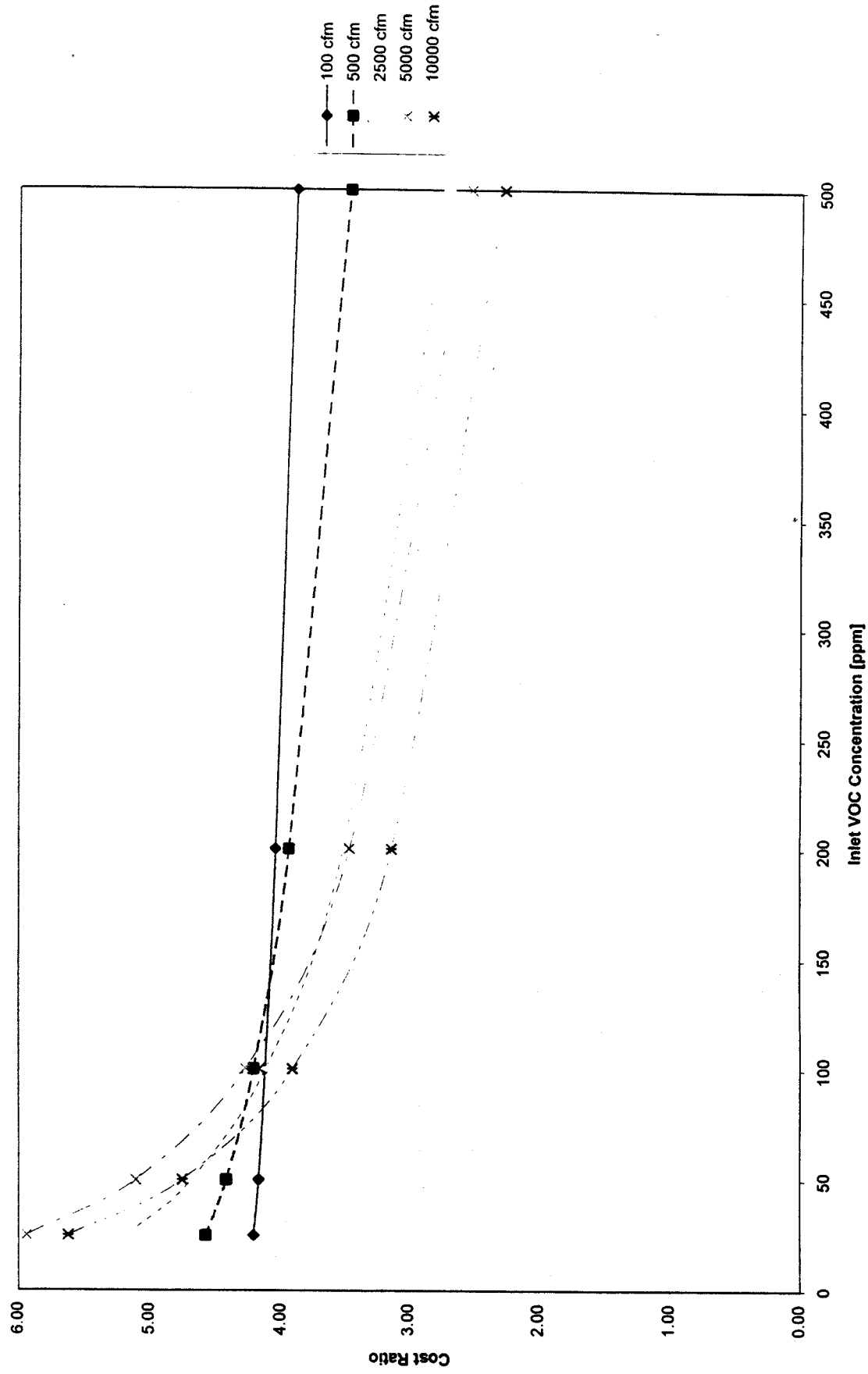


Figure 7. Thermal Incineration Cost Ratio for TCE Treatment Relative to THP

Ratio Chart 63

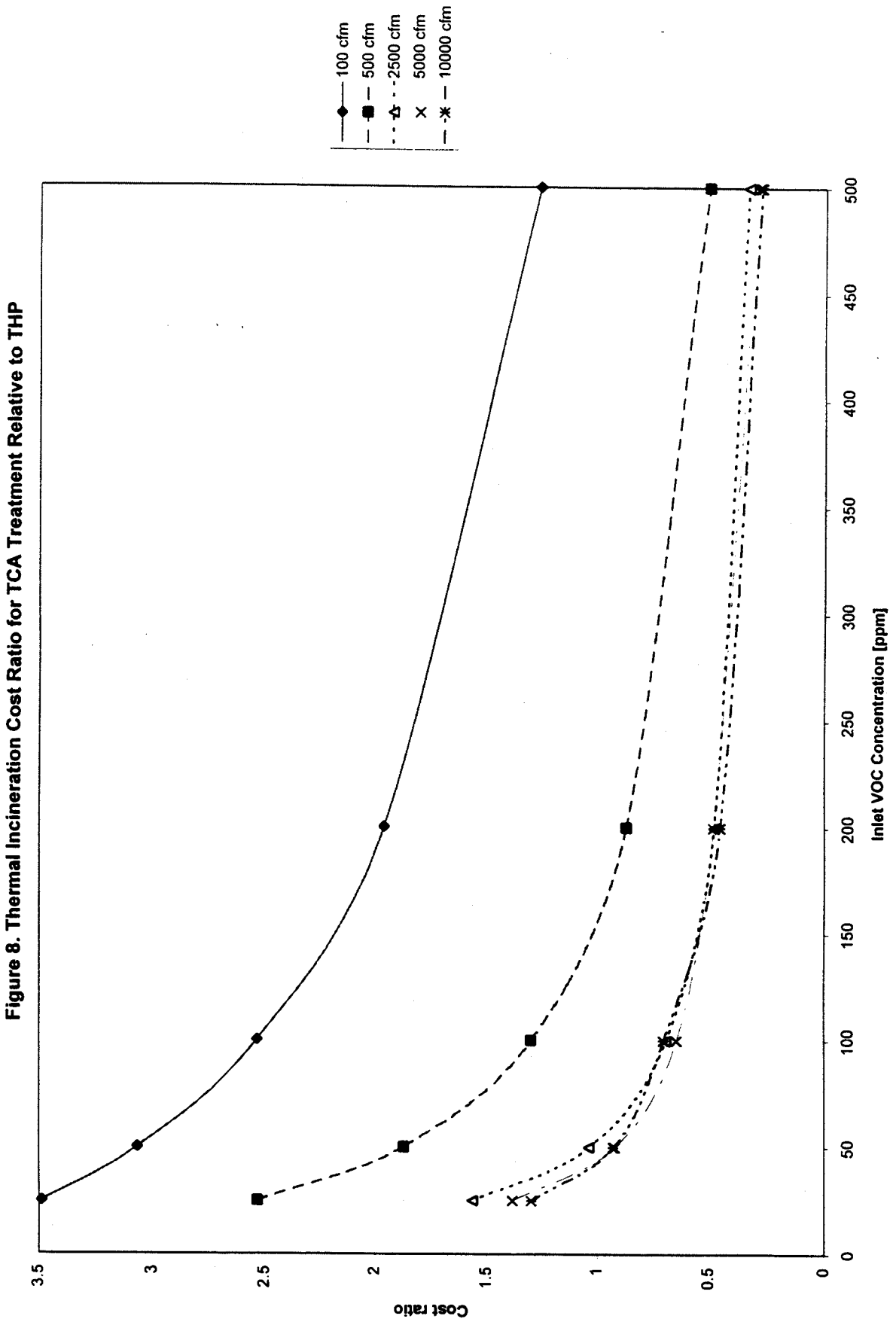


Figure 8. Thermal Incineration Cost Ratio for TCA Treatment Relative to THP

Ratio Chart 55

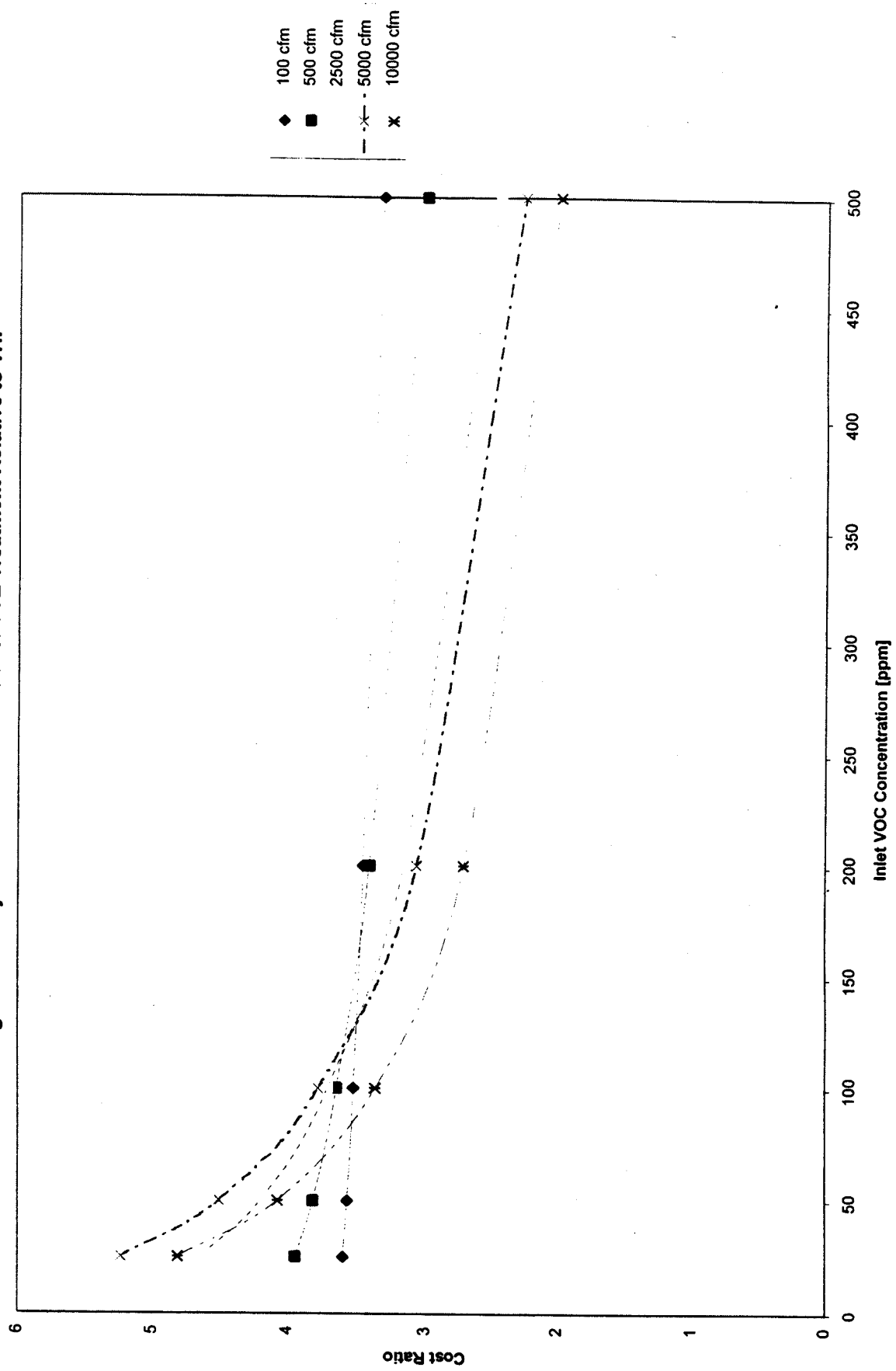
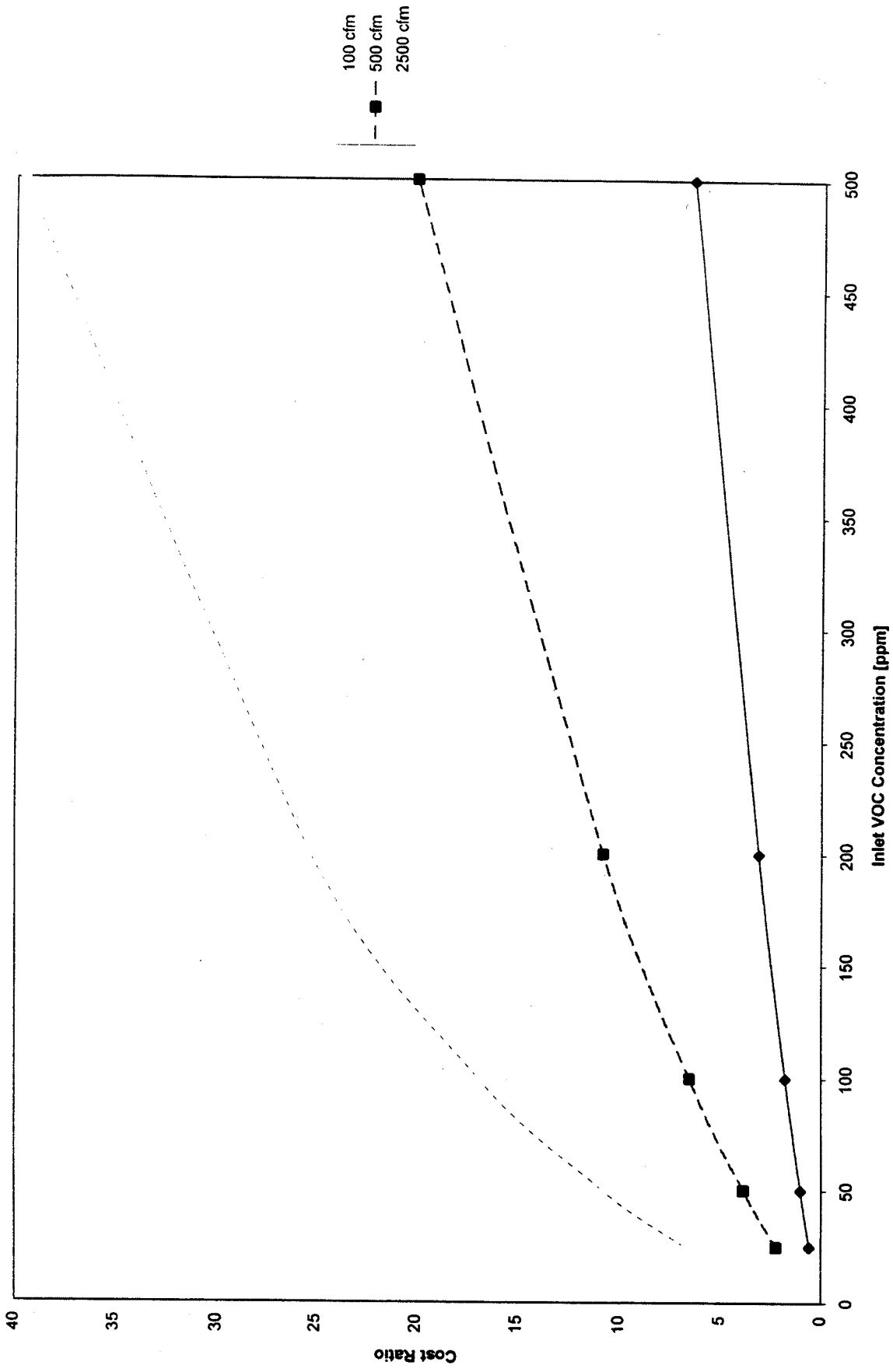


Figure 9. Catalytic Oxidation Cost Ratio for TCE Treatment Relative to THP

Ratio Chart 57

Figure 10. GAC Cost Ratio for TCE Treatment Relative to THP



Ratio Chart 65

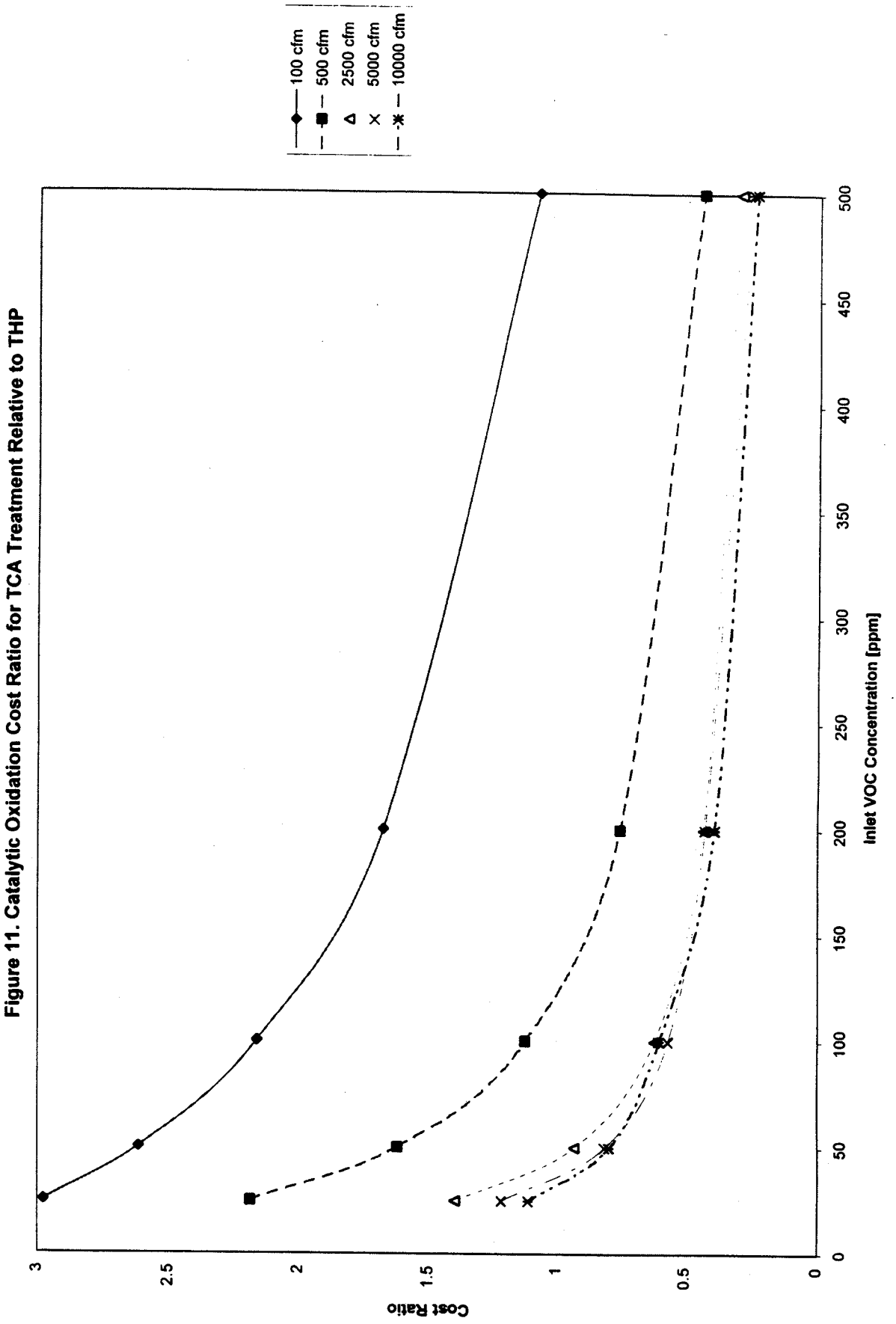


Figure 11. Catalytic Oxidation Cost Ratio for TCA Treatment Relative to THP

Ratio Chart 67

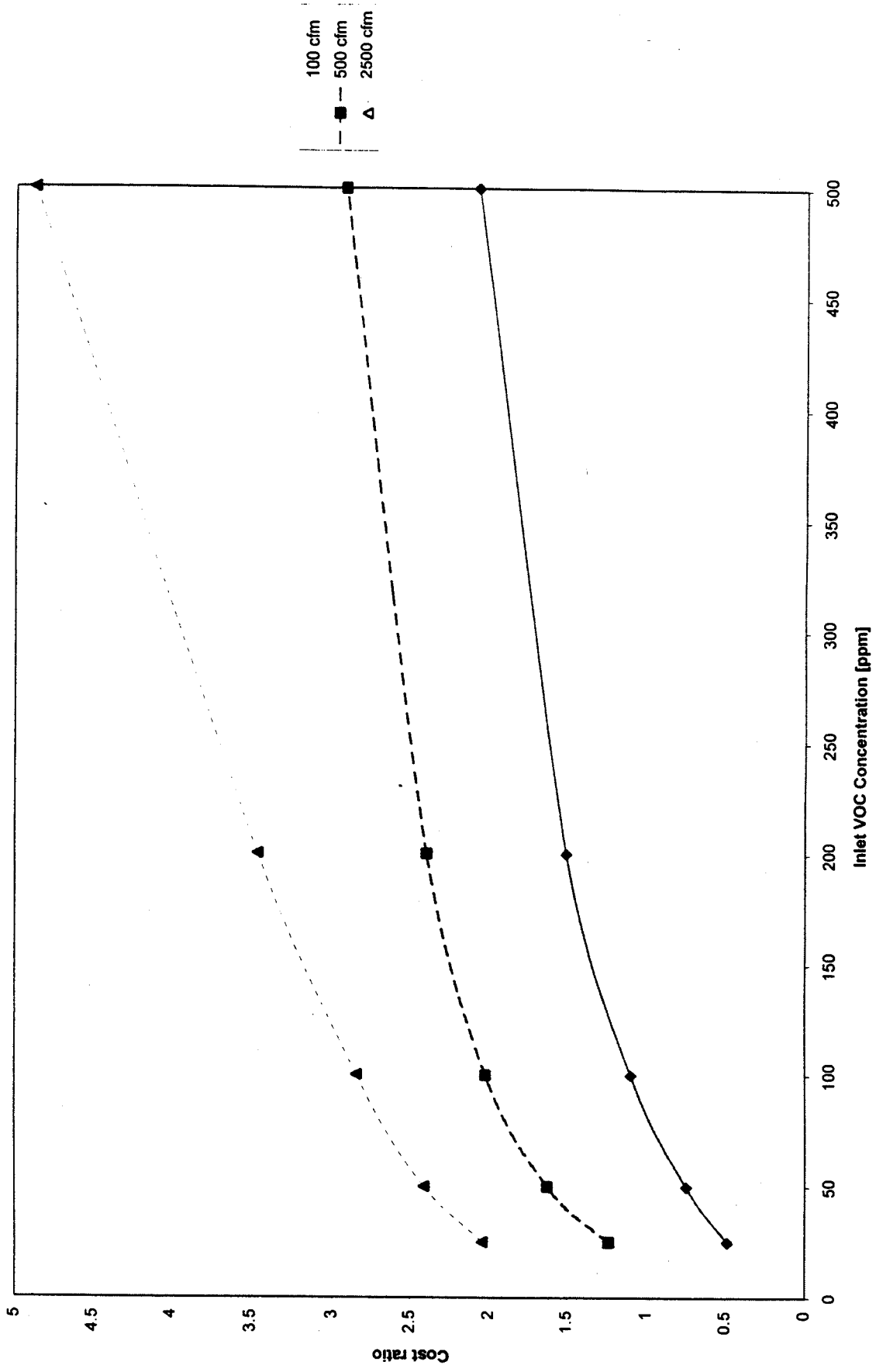


Figure 12. GAC Cost Ratio for TCA Treatment Relative to THP

Ratio Chart 58

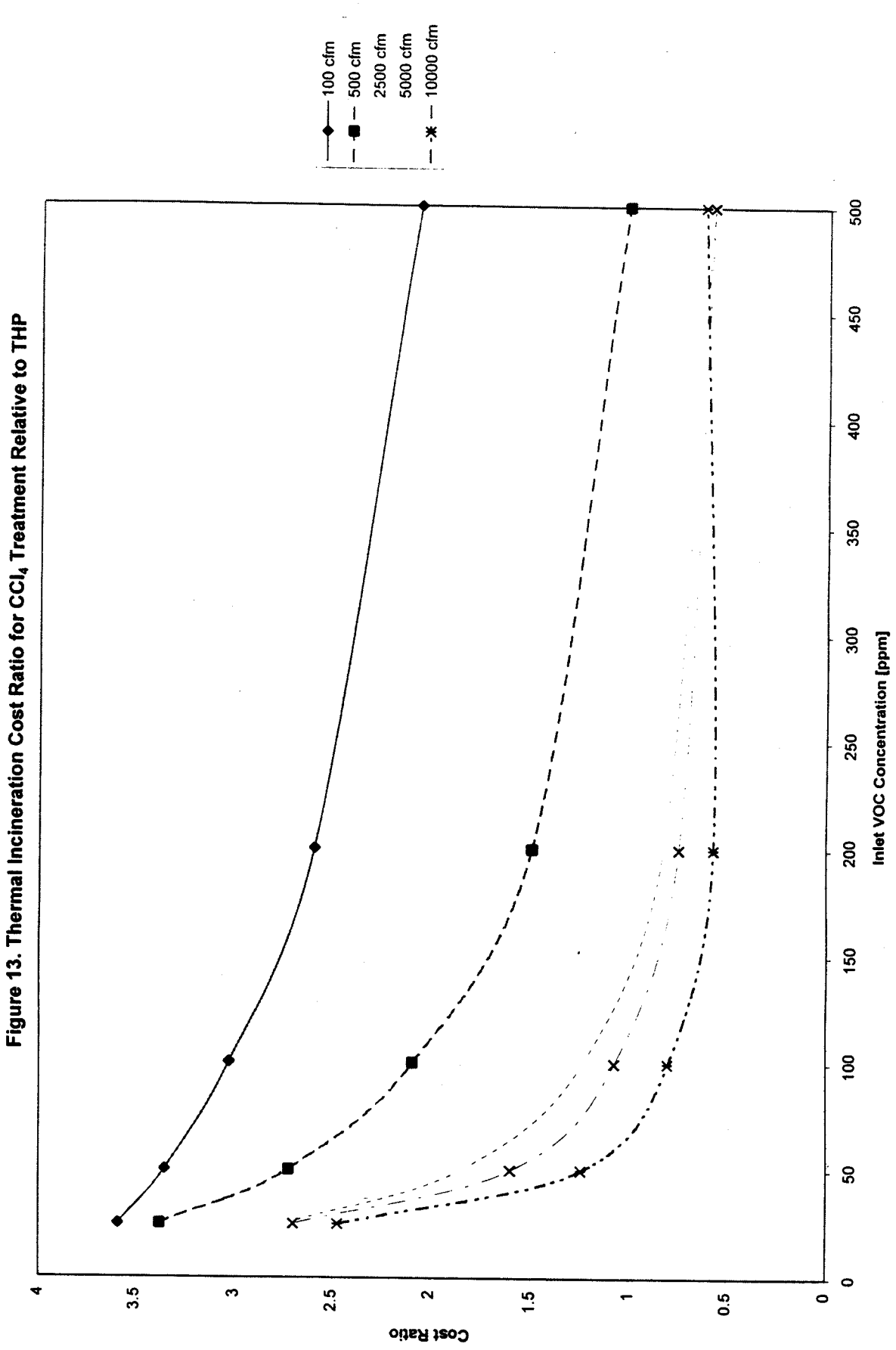


Figure 13. Thermal Incineration Cost Ratio for CCl_4 Treatment Relative to THP

Ratio Chart 30

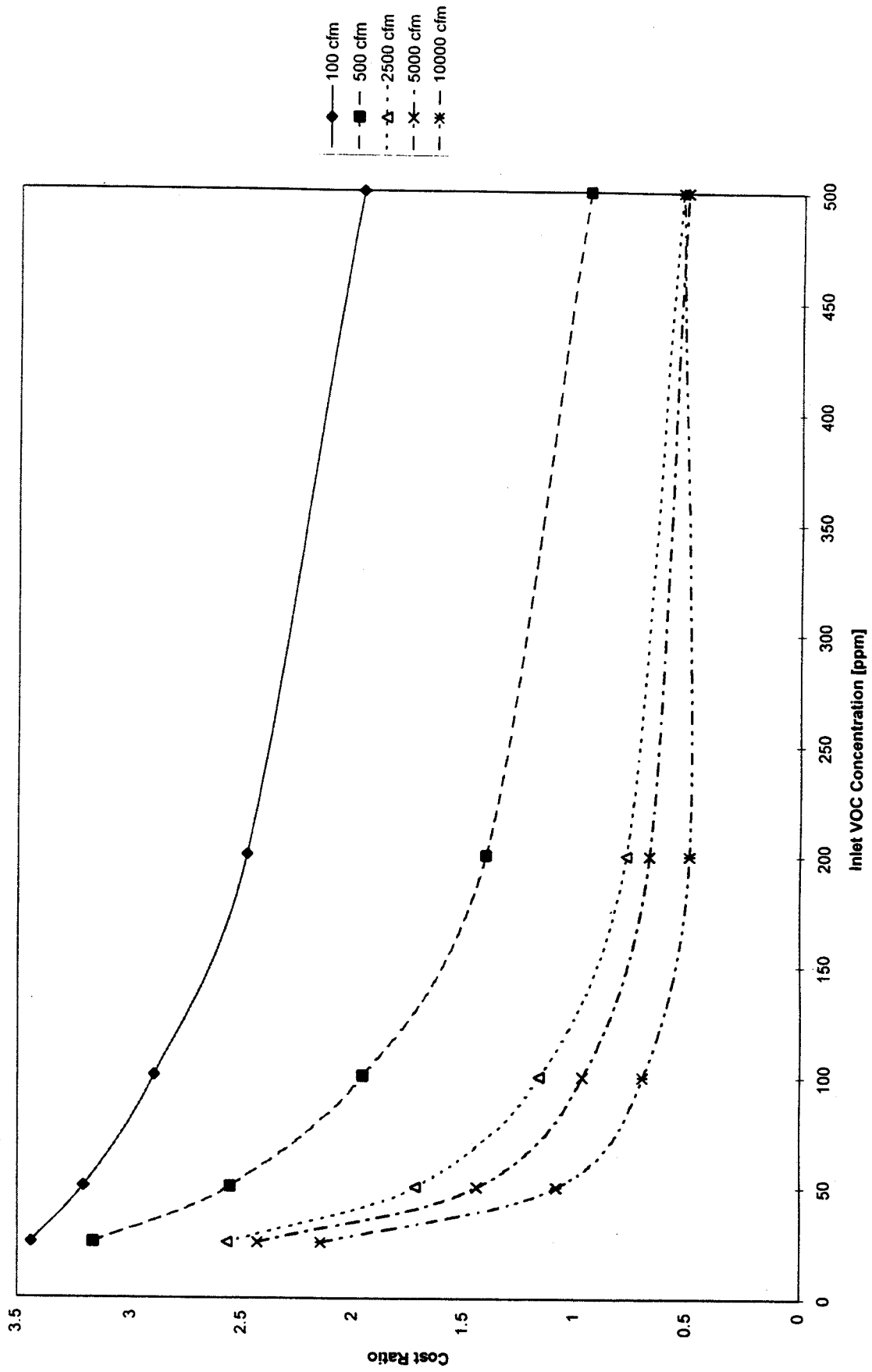


Figure 14. Catalytic Oxidation Cost Ratio for CCl_4 Treatment Relative to THP

Ratio Chart 36

Figure 15. GAC Cost Ratio for CCl_4 Treatment Relative to THP

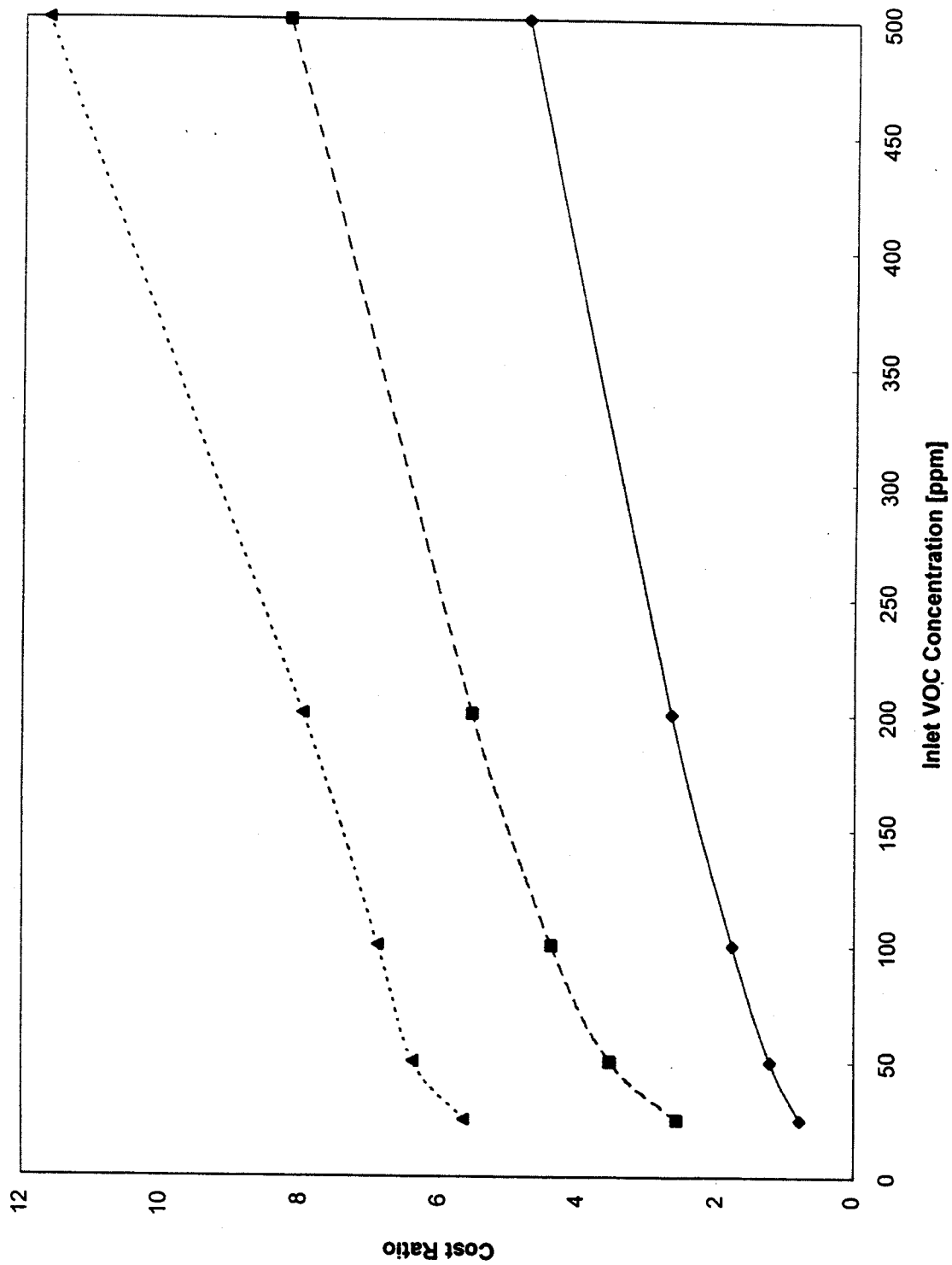


Table 7 gives the flow rate for a typical concentration of 100, and 200 ppm of TCE, CCl_4, and TCA, for which the cost of THP is equal to or less than the cost of the technology compared with (cost ratio =1).

Table 7. Flow rate for a typical concentrationof 100, and 200 ppm for which the cost ratio is equal to 1

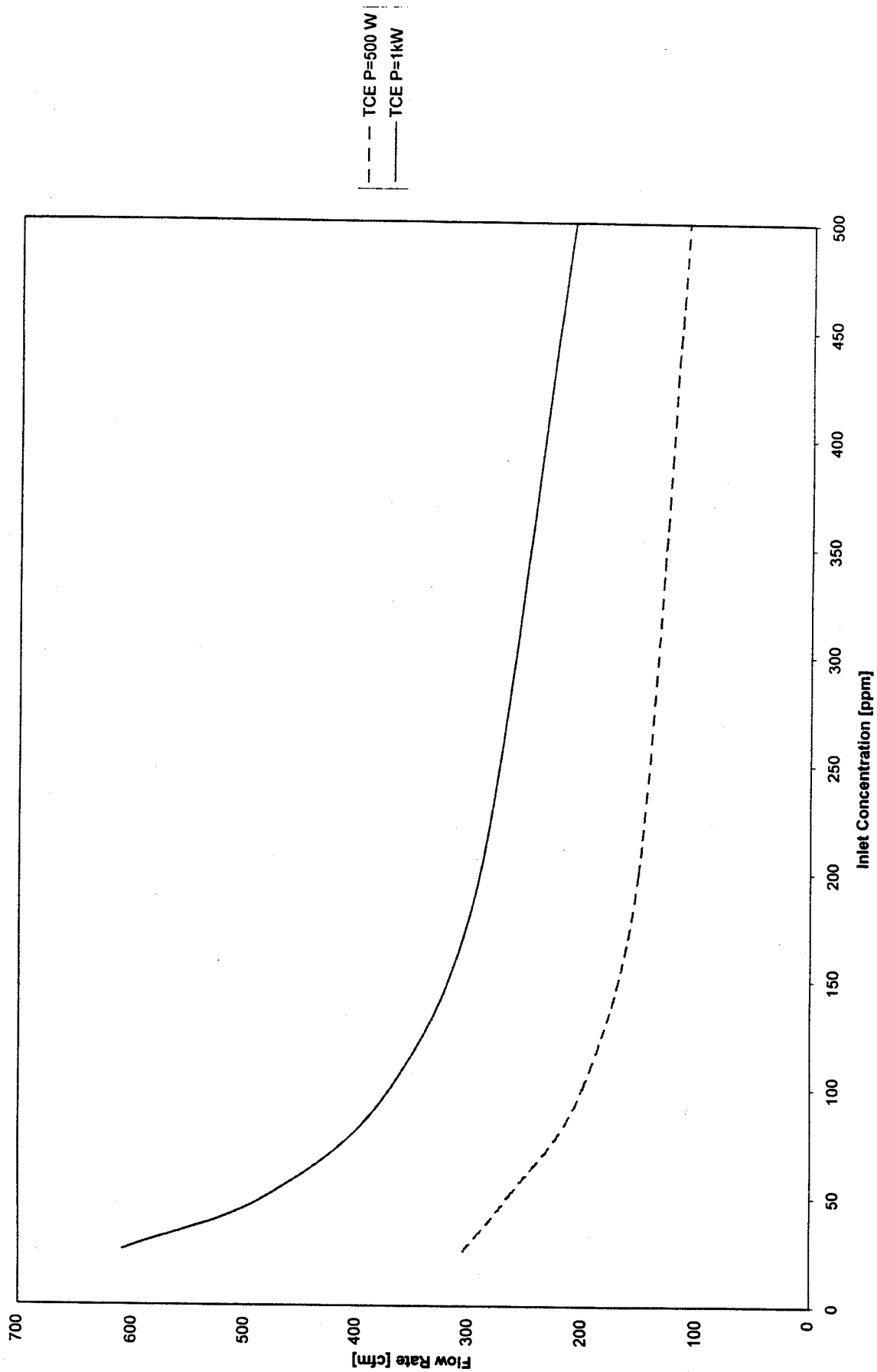
VOC	Flow rate [cfm]		Technology compared with
	100 ppm	200ppm	
TCE	0 - > 10000	0 - > 10000	Thermal incineration
	0 - > 10000	0 - > 10000	Catalytic oxidation
	> 100	> 100	GAC
CCl_4	< 5000	< 2500	Thermal incineration
	< 5000	< 2500	Catalytic oxidation
	> 100	>100	GAC
TCA	< 2500	< 500	Thermal incineration
	< 2500	< 500	Catalytic oxidation
	> 100	> 100	GAC

For TCE, the cost ratio between the two thermal technologies and THP is higher than 1 for the flow rate range for which the comparison is made (0 to 10,000 cfm). Therefore, the flow rates upper limit given in table 7 for TCE is not exclusive.

For applications where the amortization period is short, or with low flow rates, for which GAC is currently the only alternative, the modular electron beam technology can open up a new range of applications with relatively low capital cost. Figures 16, 17, and 18 give flow rate and inlet concentration ranges respectively for TCE, TCA, and CCl_4 for an electron beam generator with power of 500 and 1000 Watts.

Sheet2 Chart 14

Figure 16. Flow Rate and Inlet Concentration Ranges for TCE for 500 and 1000 W Electron Beam Generator



Sheet2 Chart 16

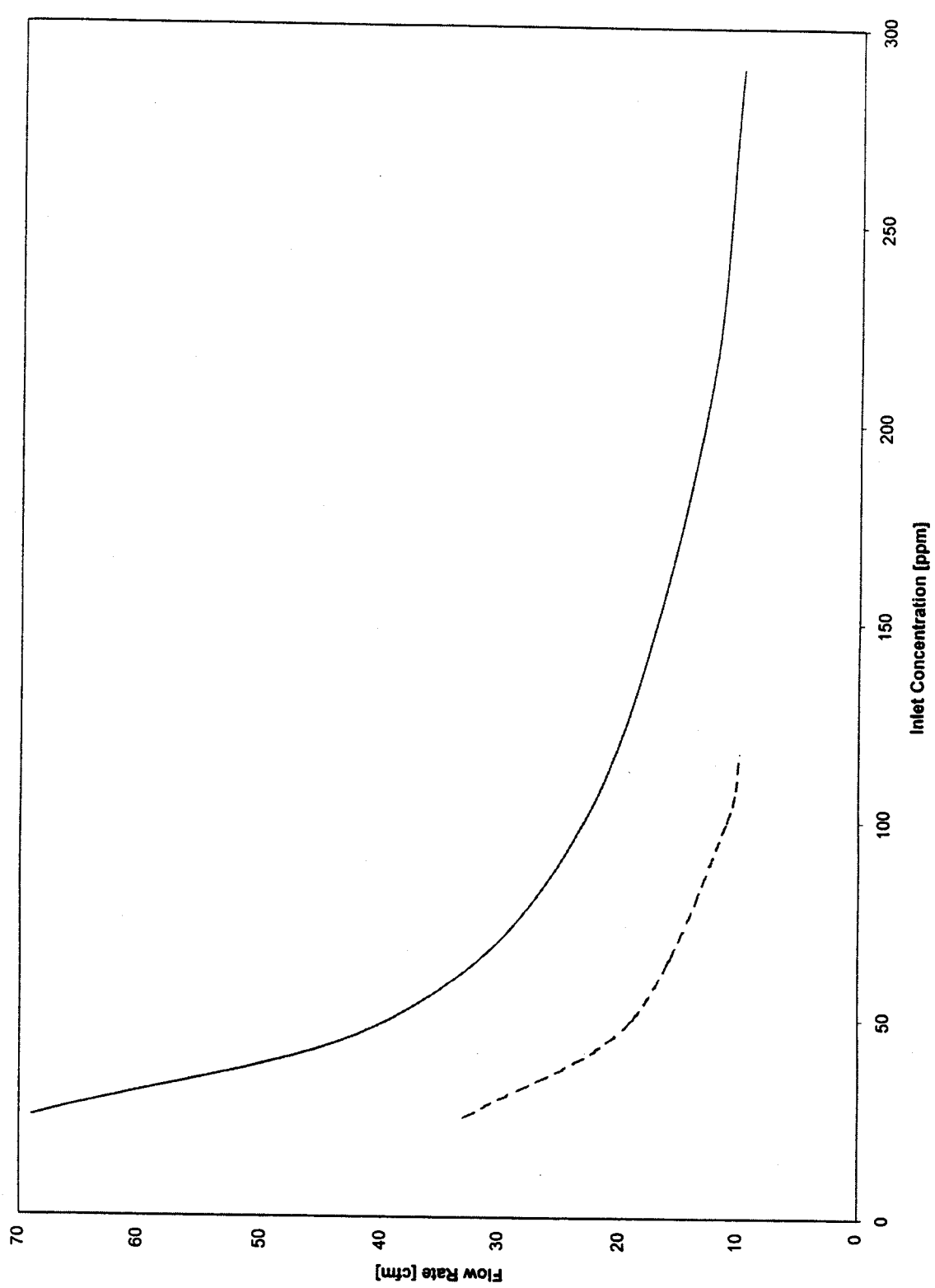


Figure 17. Flow Rate and Inlet Concentration Ranges for TCA for 500 and 1000 W Electron Beam Generator

Sheet2 Chart 15

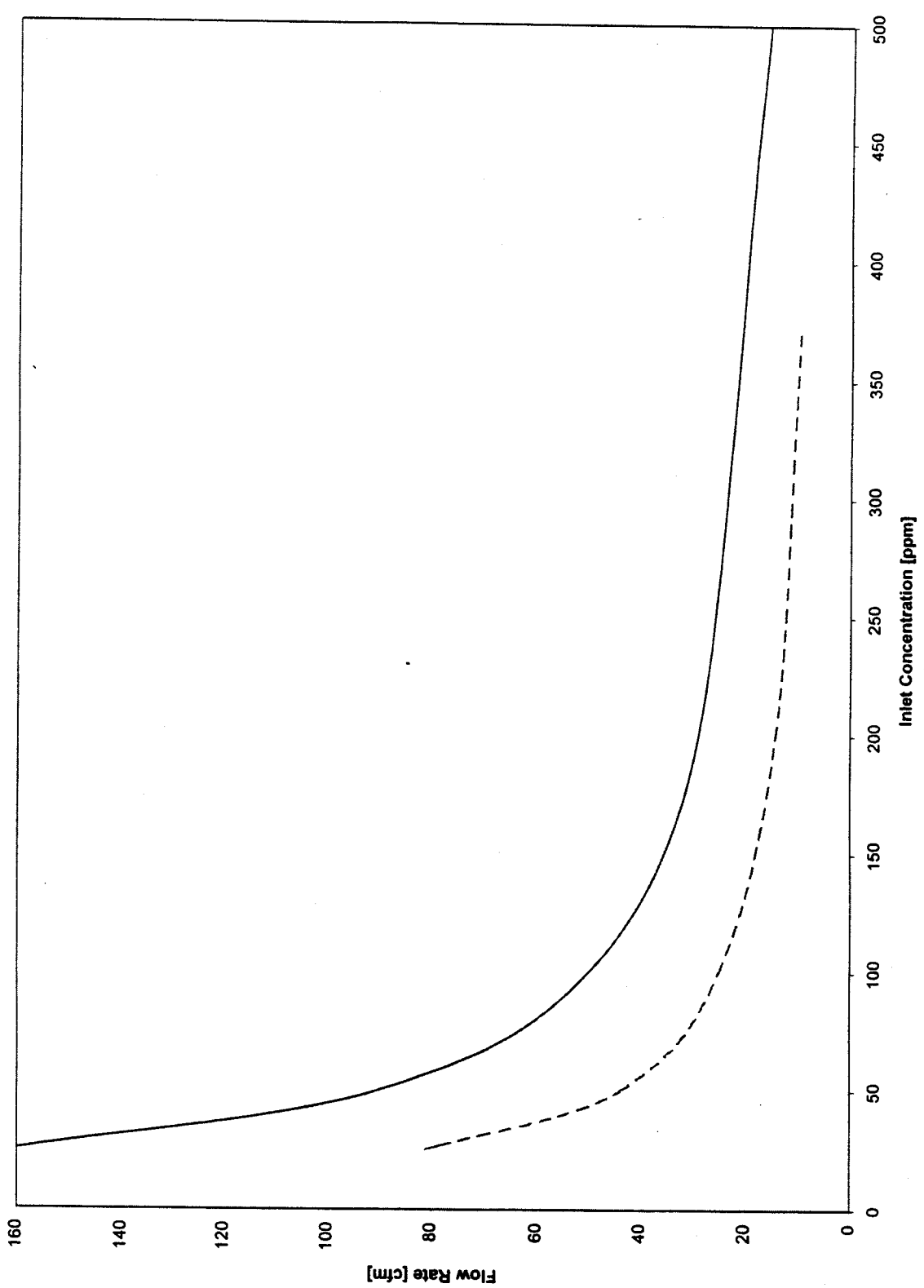


Figure 18. Flow Rate and Inlet Concentration Ranges for CCl_4 for 500 and 1000 W Electron Beam Generator

4. Market Opportunities

It is one of the objectives of Thermo Power's work with MIT to develop reliable estimates of the market character and potential size for the Tunable Hybrid Plasma technology. Thermo Process Systems, an environmental services subsidiary of Thermo Electron, has estimated the total environmental services market at $27 billion. Thermo Power plans to work with other Thermo Electron subsidiaries to develop specific potential market information for the Tunable Hybrid Plasma technology as part of our commercialization study.

Thermo Remediation has treatment facilities located on the East and West coasts of the United States. In 1994, Thermo Remediation had $30M in revenue from remediation as the company expanded its network of treatment facilities and broadened its services to include recycling of waste fluids through its Thermo Fluids business. Thermo Remediation has also very recently acquired Remediation Technologies, Inc. of Concord, MA, a company which employs pump-and-treat technologies for soil remediation. The support technologies employed and markets addressed by Remediation Technologies are closely related to those for the Tunable Hybrid Plasma technique, and we expect Remediation Technologies to be a valuable resource in developing reliable market estimates. This acquisition provides a potential path to commercialization within Thermo Electron.

In addition to the market size information, Thermo Power's access to resources in other Thermo Electron subsidiaries will provide avenues by which to evaluate our ability to penetrate the soil VOC remediation markets currently dominated by thermal incineration, catalytic oxidation, and granulated activated carbon technologies. We will also explore potential commercial applications of the technology, for example, for the treatment of low-level VOC contamination of indoor air in industrial environments.

As an example of the size of one portion of the VOC remediation market to which the Tunable Hybrid Plasma technology may be applied, much of America's fuel supply rests in underground storage tanks (USTs), and the overwhelming majority are made of and connected by steel that is slowly corroding. The U.S. Environmental Protection Agency currently regulates more than 2,000,000 USTs and another 3,000,000 or more are small tanks not at present subject to federal oversight. From the regulated tanks, the EPA cumulatively logged nearly a quarter million confirmed releases by the end of 1993. Many more leaks may be unreported. Approximately 185,000 cleanups had begun by the end of 1993, but only 91,000 had been completed, and the gap between confirmed releases and completed cleanups continued to widen in 1994.

The National Research Council estimates that there are 300,000-400,000 sites in the United States where the groundwater may be chemically contaminated from such sources as industrial wastes, leaking storage tanks, or accidental spills [12]. Among the principal groundwater contaminants are trichloroethylene, tetrachloroethylene, low molecular weight aromatics, and other compounds yielding to pump and treat remediation strategies. Total cost projections for cleaning up these contaminated sites range up to $1 trillion, making it critical to develop the most technologically appropriate, most environmentally sound, and most cost-effective approaches possible.

5. Future Development Directions

The future development for THP technology can be seen in several different directions. These directions can be identified as follows:

- Treatment of:
  - VOC mixtures
  - Hydrocarbons
  - Semiconductor processing off-gases

- CFCs and PFCs
- H_2S
- PCBs

• Effect of an external electric field and additives on the energy expense for different compounds

• Surface treatments

• Thin film deposition

• Hybrid systems using electron-beam plasma and other technologies

6. Potential Applications

6. 1 Air Stripping of Contaminated Water

Because of the widespread use and disposal of hazardous chemicals on land, the groundwater contamination problem is potentially very large. Surface and groundwater supplies are know with chlorohydrocarbon concentrations up to 1 mg/liter, and trihalomethane levels in some areas exceed the federal standard of 0.1 mg/liter [13]. In some cases industrial solvents can pollute groundwater in concentrations up to 10% of the saturation concentration of the solvent in water. Table 8 gives the 25 most frequently detected groundwater contaminants at hazardous waste sites [12].

The most common technology used for treating contaminated groundwater is pump-and-treat systems. Contaminated groundwater is extracted from the subsurface and treated using any of a number of methods that have been tested for removing contaminants from drinking water and industrial and municipal waste water. For example, air strippers can remove volatile contaminants, granular activated carbon can remove dissolved organic contaminants, and biological systems can remove biodegradable contaminants. Once treated, the water may be discharged to a surface water body or re-injected underground.

Table 8. Most frequently detected ground-water contaminants at hazardous waste sites

Rank	Compound	Common sources
1	Trichloroethylene	Dry cleaning; metal degreasing
2	Lead	Gasoline (prior to 1975); mining; construction material (pipes); manufacturing
3	Tetrachloroethylene	Dry cleaning; metal degreasing
4	Benzene	Gasoline; manufacturing
5	Toluene	Gasoline; manufacturing
6	Chromium	Metal plating
7	Methyl chloride	Degreasing; solvent; paint removal
8	Zinc	Manufacturing; mining
9	1,1,1 Trichloroethane	Metal and plastic cleaning
10	Arsenic	Mining; manufacturing
11	Chloroform	Solvents
12	1,1 Dichloroethane	Degreasing, solvents
13	1,2 Dichloroethane, trans	Transformation product of 1,1,1 trichloroethane
14	Cadmium	Mining; plating
15	Manganese	Manufacturing; mining
16	Copper	Manufacturing; mining
17	1,1 Dichloroethene	Manufacturing
18	Vinyl chloride	Plastic and record manufacturing
19	Barium	Manufacturing; energy production
20	1,2 Dichloroethane	Metal degreasing; paint removal
21	Ethylbenzene	Styrene and asphalt manufacturing; gasoline
22	Nickel	Manufacturing; mining
23	Di(2-ethylhexyl)phthalate	Plastic manufacturing
24	Xylenes	Solvents; gasoline
25	Phenol	Wood treating; medicines

The air stripping used for volatile organic compounds transforms the contaminant from its dissolved phase to a gas phase. Due to the low concentrations of the solvents in the water, a Henry's Law approach may be used to design a stripping column, with results accurate to about a factor of 2.

Henry's Law relates the equilibrium partial pressure of a species in the air phase to the concentration of that species in the liquid phase.

$$P_a = H_a X_a$$

Where P_a is the partial pressure of species a, H_a is the Henry's constant of species a, and X_a is the concentration of species a in the liquid phase. Note that Henry's Law is a very simple thermodynamic approximation, which is generally only applicable at low concentrations. The VOC concentration in the air stream coming out of the stripper depends on the air flow rate, the nature of the VOC, and its concentration in water.

THP systems can be used to treat contaminated air streams from air stripping instead of using traditional technologies such as GAC, thermal incineration , and catalytic oxidation.

6. 2 Soil Remediation

Most of the contaminants encountered in contaminated soils are the same as those given in Table 8. The most often mean used to recover volatile organic compounds from contaminated soils is vapor extraction technology. The soil is flushed with air by applying vacuum at sealed well-head. The air stream contacts contaminants - which may be present as a nonaqueous-phase liquid, dissolved in water in the soil pores, or associated with the soil - and mass transfer of the contaminant to the air occurs. The

contaminated air stream is pumped to the surface where it can be processed with various remediation technologies such as GAC, thermal incineration, and catalytic oxidation.

The soil vapor extraction (SVE) technology is likely to be successful if the contaminant's boiling point is less than 150° C or if its vapor pressure (evaluated at the sub-surface temperature) is greater than about 5×10^{-4} atm [14].

Typical flow rates for soil vapor extraction systems are 500 to 2500 cfm. VOC concentrations may start at as high as the VOC vapor pressure and rapidly decline to about 50 to 200 ppm for long-term remediation.

The THP technology can be economically used to process contaminated air streams from soil vapor extraction systems.

6. 3 Industrial Off-gases

The next challenge will be to eliminate or minimize industrial emissions off-gases. These emissions come usually from traditional industries such as paper and textile industries as well as modern industries such as the semiconductor industry. THP systems can be easily designed to treat industrial off-gases from a few cfm to several thousand cfm with varying inlet concentrations.

Industrial flow rates of off-gases can vary from a few cfm to tens of thousands of cfm with concentrations from a few ppm to thousands of ppm.

One of the potential applications of THP systems is the destruction of tetrachloroethylene emitted by the dry cleaning industry where flow rates are very low (few cfm). Modular electron beam technology allows the building of small, low power, compact, and low cost THP systems for such applications.

7. Industrial Partner

Thermo Electron Corporation, a Fortune 300 Company, is a world leader in environmental monitoring and analysis instruments, alternative energy systems, and other products and services related to environmental quality, health, and safety. Thermo Electron has a long and successful history of developing and commercializing new technologies, and it has an infrastructure geared for further expansion. The corporation's strategy includes "spinning out" promising new ventures as public subsidiaries, and the extraordinary return on investment in these spinouts (22% weighted average compound annual return) encourages additional innovation and growth. Thermo Electron was selected R&D Magazine's first "Corporation of the Year" in 1989 for this philosophy and its ongoing success.

Thermo Power, a Thermo Electron subsidiary, conducts research and develops products in advanced energy, combustion, and environmental technologies. It also manufactures and markets industrial refrigeration systems, natural gas-fueled cooling and cogeneration units, marine engines, and low emission natural gas engines for vehicles and industrial applications. Thermo Remediation, another subsidiary of Thermo Electron, is a world leader in soil remediation, with treatment facilities distributed on the East and West coasts of the United States. In 1994, Thermo Remediation grew 44% as the company expanded its network of soil remediation sites and broadened its services to include recycling of waste fluids.

Thermo Power takes seriously exploring and developing the commercial potential of MIT's electron beam plasma remediation technology, and it considers non-thermal plasma technologies, in general, to be among its most promising new areas for commercial development. Thermo Power's unique combination of expertise in non-thermal plasma technology and in environmentally sound energy production and management make it optimally positioned to commercialize the Tunable Hybrid Plasma Technology.

Thermo Power's non-thermal plasma development effort is being performed by its Tecogen Division, which has facilities located in Waltham and Marlborough, MA. Tecogen employs 93 people and has 72,000 ft^2 of office, laboratory, and prototype manufacturing space, approximately two-thirds of which is for R&D activities, including approximately 25,000 ft^2 of laboratory area devoted to R&D projects. The facility contains test areas with enclosed test cells, fabrication and assembly areas, and a prototype shop. Instrumentation is available for experimental measurements such as temperature, pressure, flow, humidity, flue gas analysis, and electronic analysis and troubleshooting.

Tecogen has an experienced design and drafting (CAD) department capable of producing all designs and drawings necessary to support new product development. It also maintains a fully staffed prototype machine shop capable of performing a wide range of machining operations including CNC milling, EDM, cylindrical/surface grinding, jig boring, high precision lathe work up to 32-inch diameter, and a MIL Standard inspection station. The electronics department includes all necessary capabilities to outfit, test, and troubleshoot custom or packaged microprocessor controllers.

To support engineering analysis and data acquisition, Tecogen has a range of commercial software for calculations in thermodynamics, chemical kinetics, fluid mechanics, and finite element analysis, in addition to more general programming languages.

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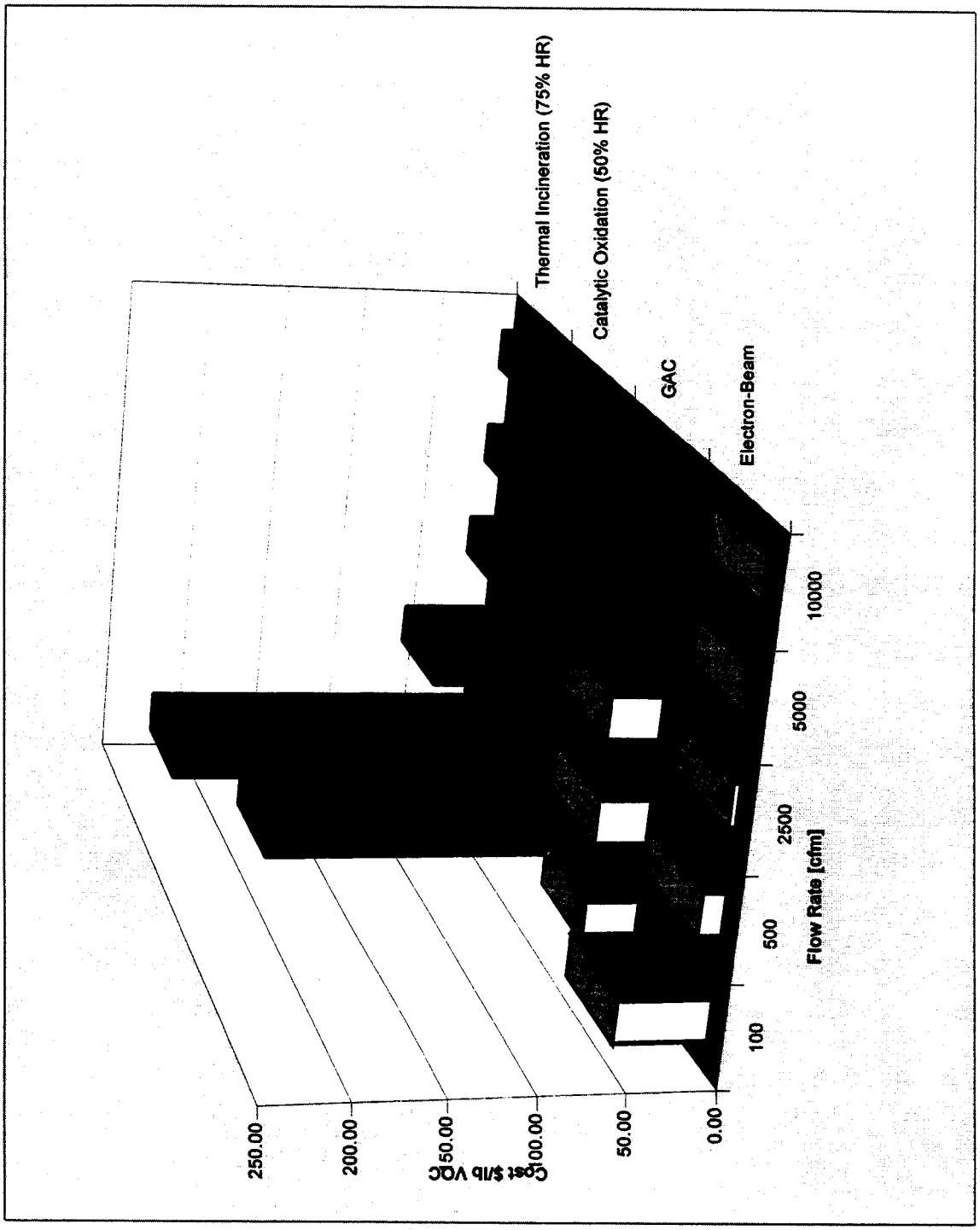
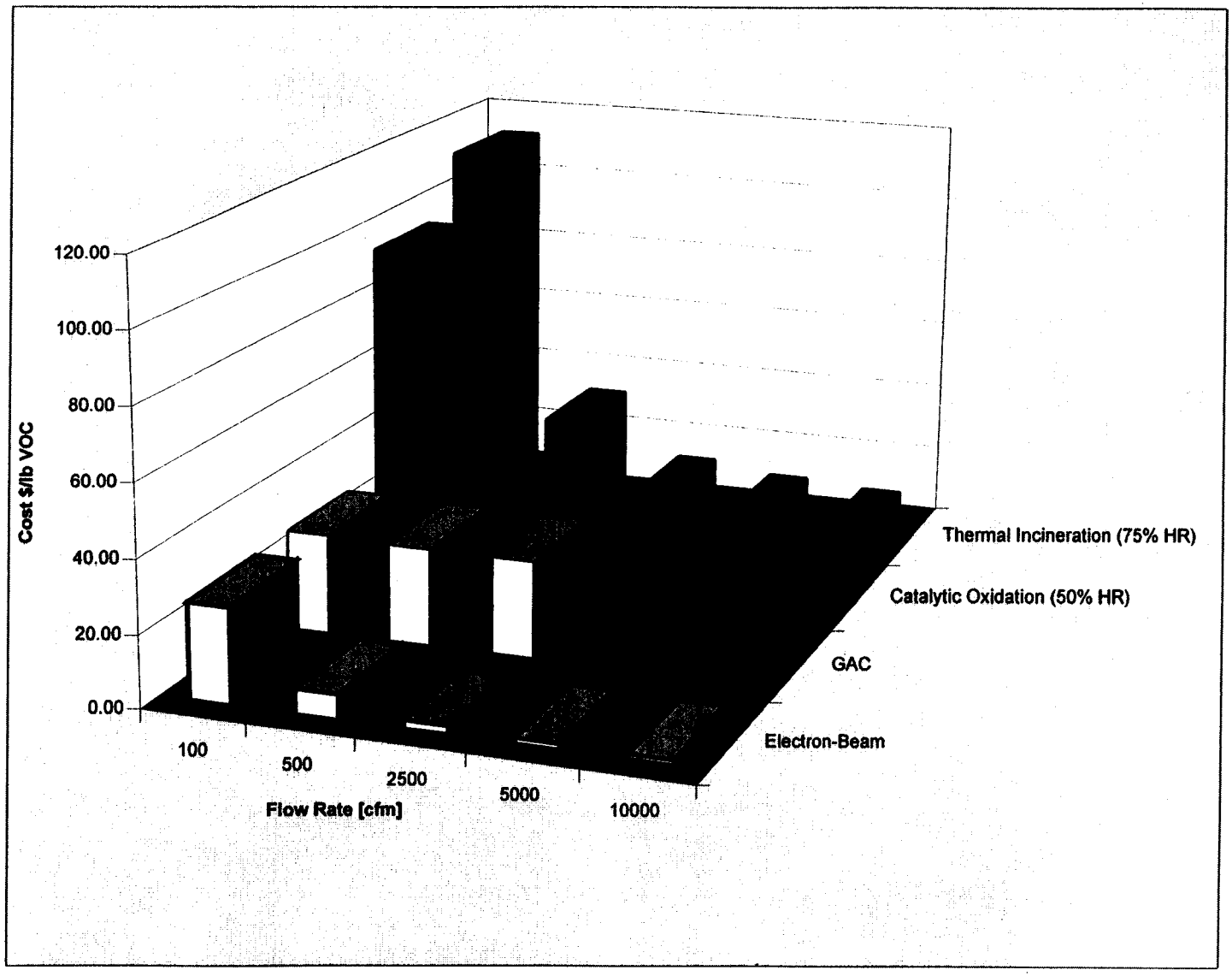
Appendix A

Compare Chart 20

A1. Cost Estimate for Destruction of 25 ppm TCE

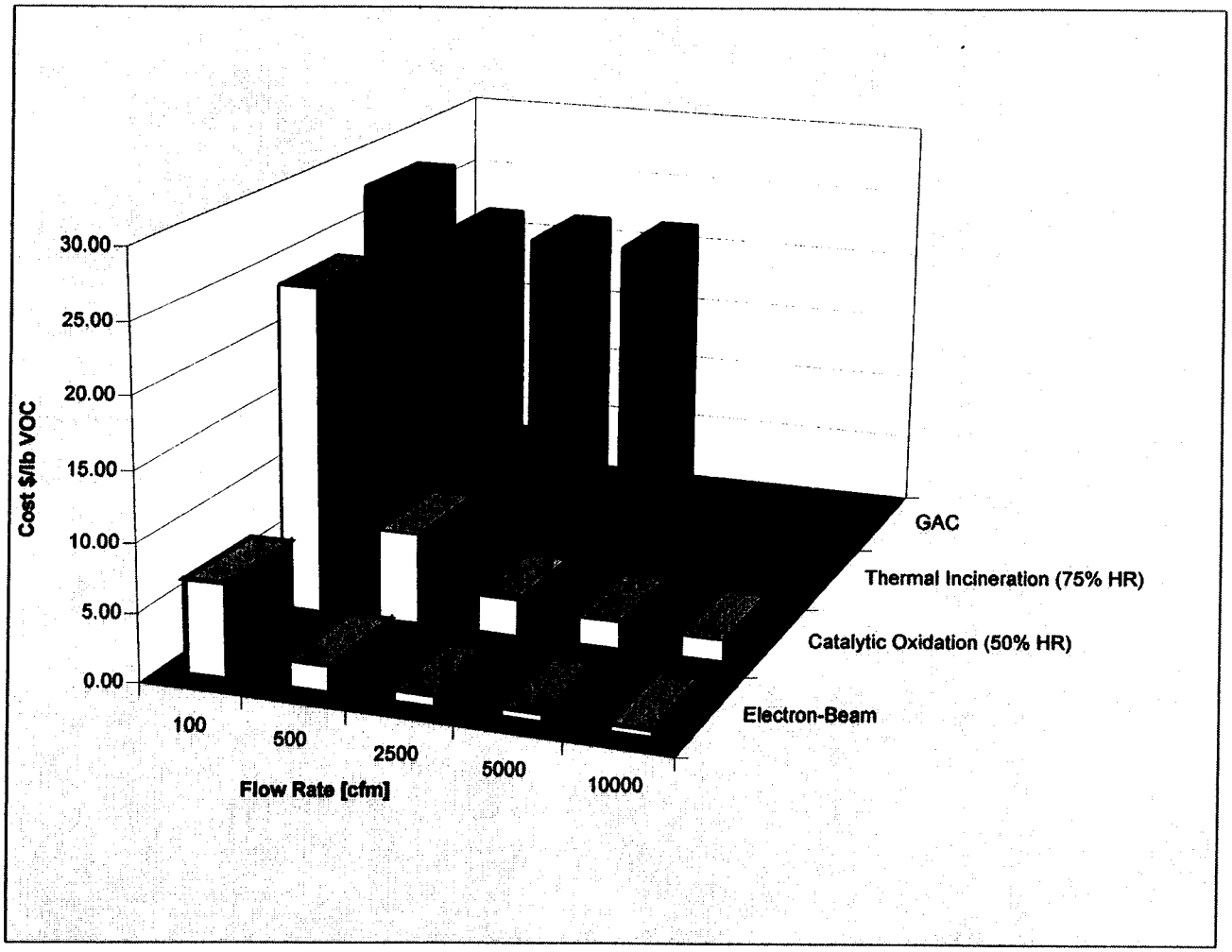


A2. Cost Estimate for Destruction of 50 ppm TCE



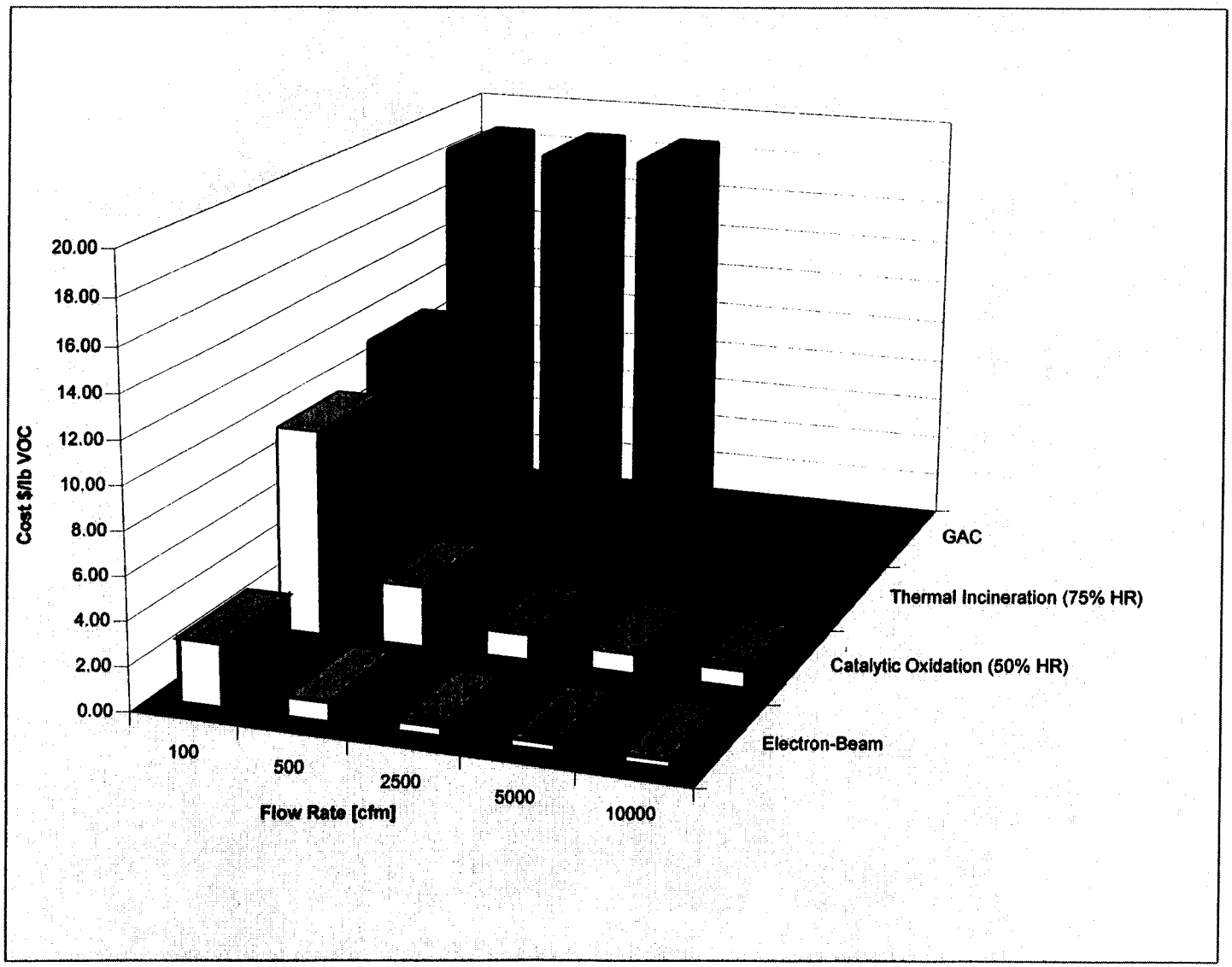
Compare Chart 27

A3. Cost Estimate for Destruction of 200 ppm TCE



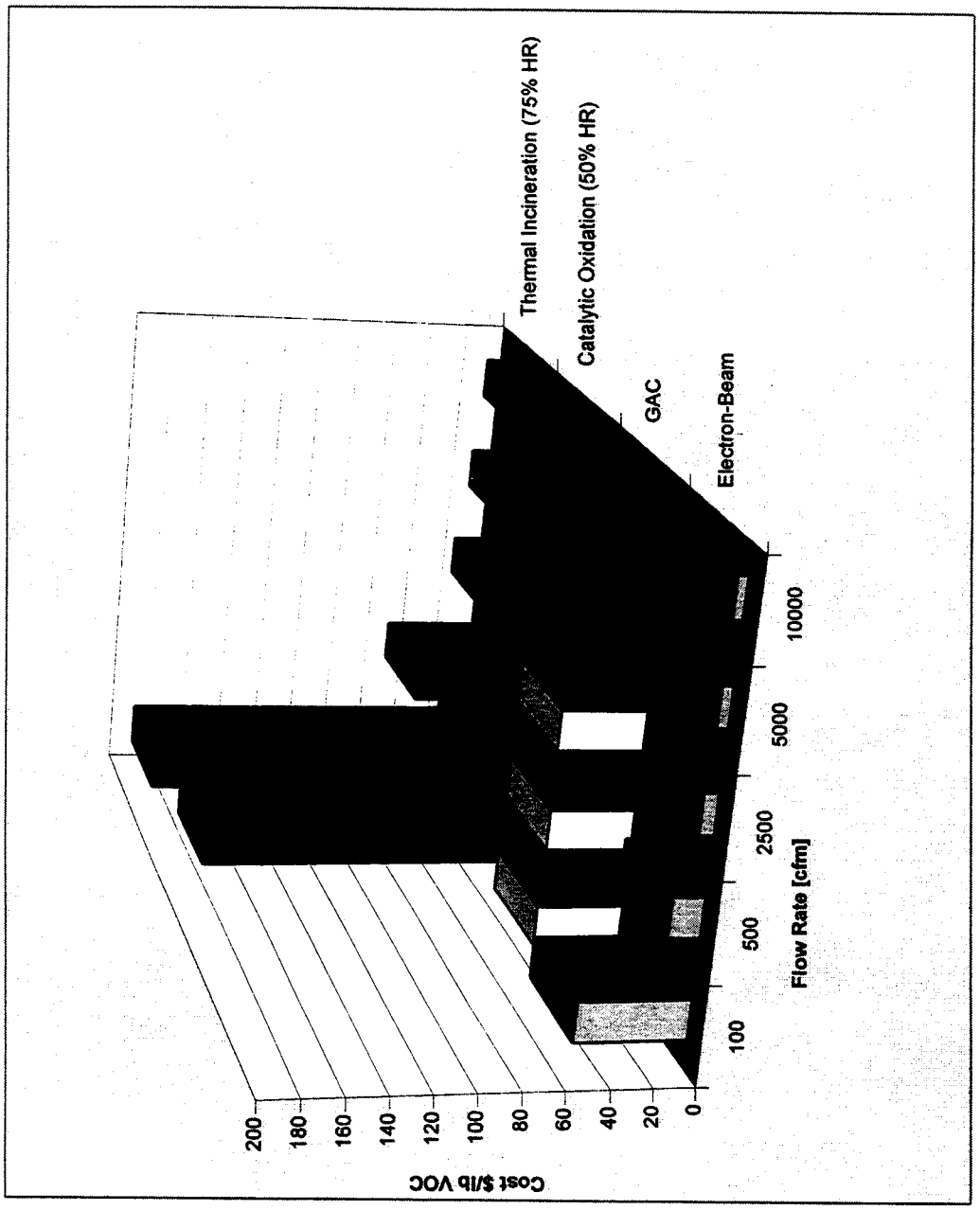
Compare Chart 33

A4. Cost Estimate for Destruction of 500 ppm TCE

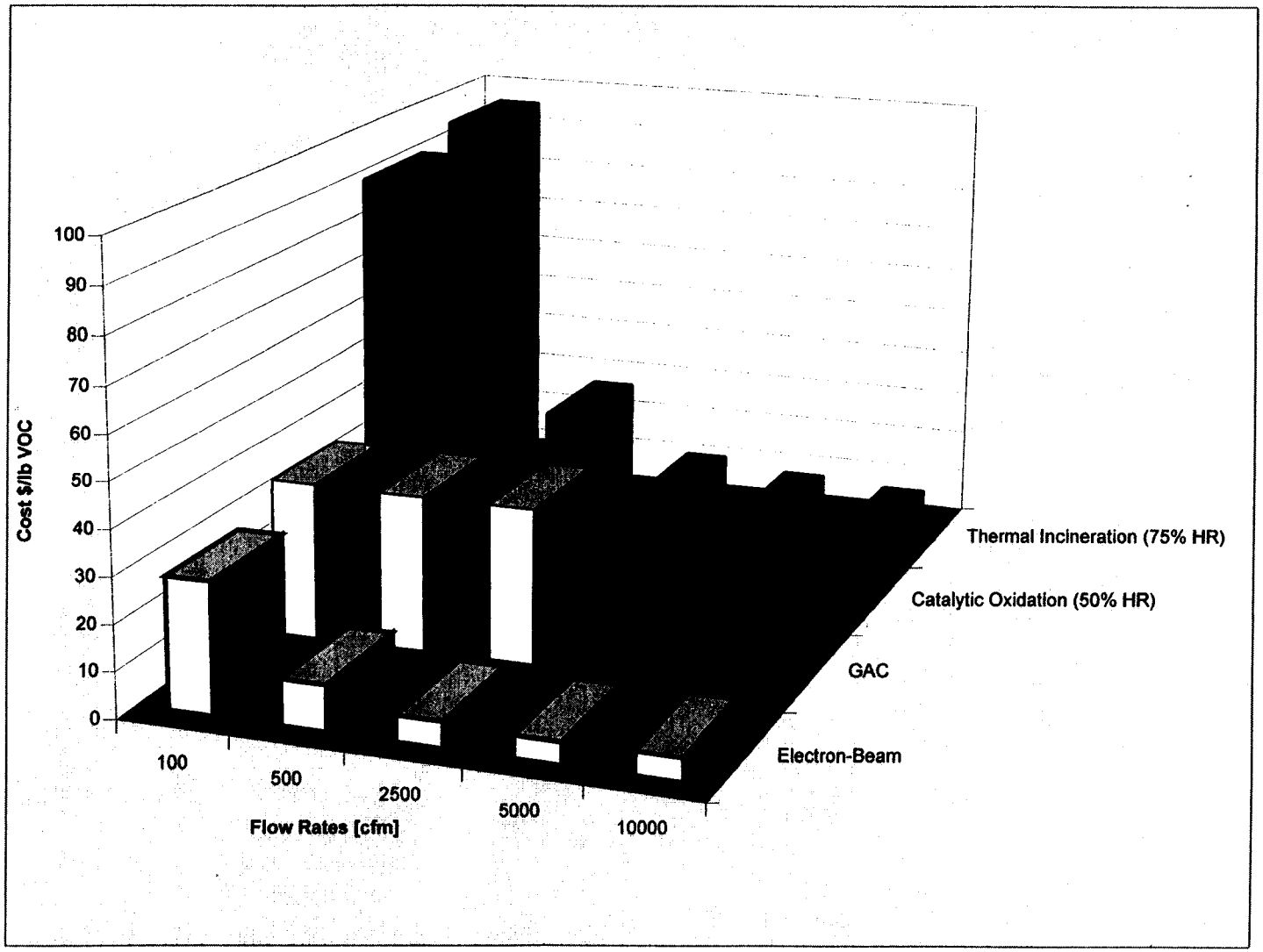


Compare Chart 28

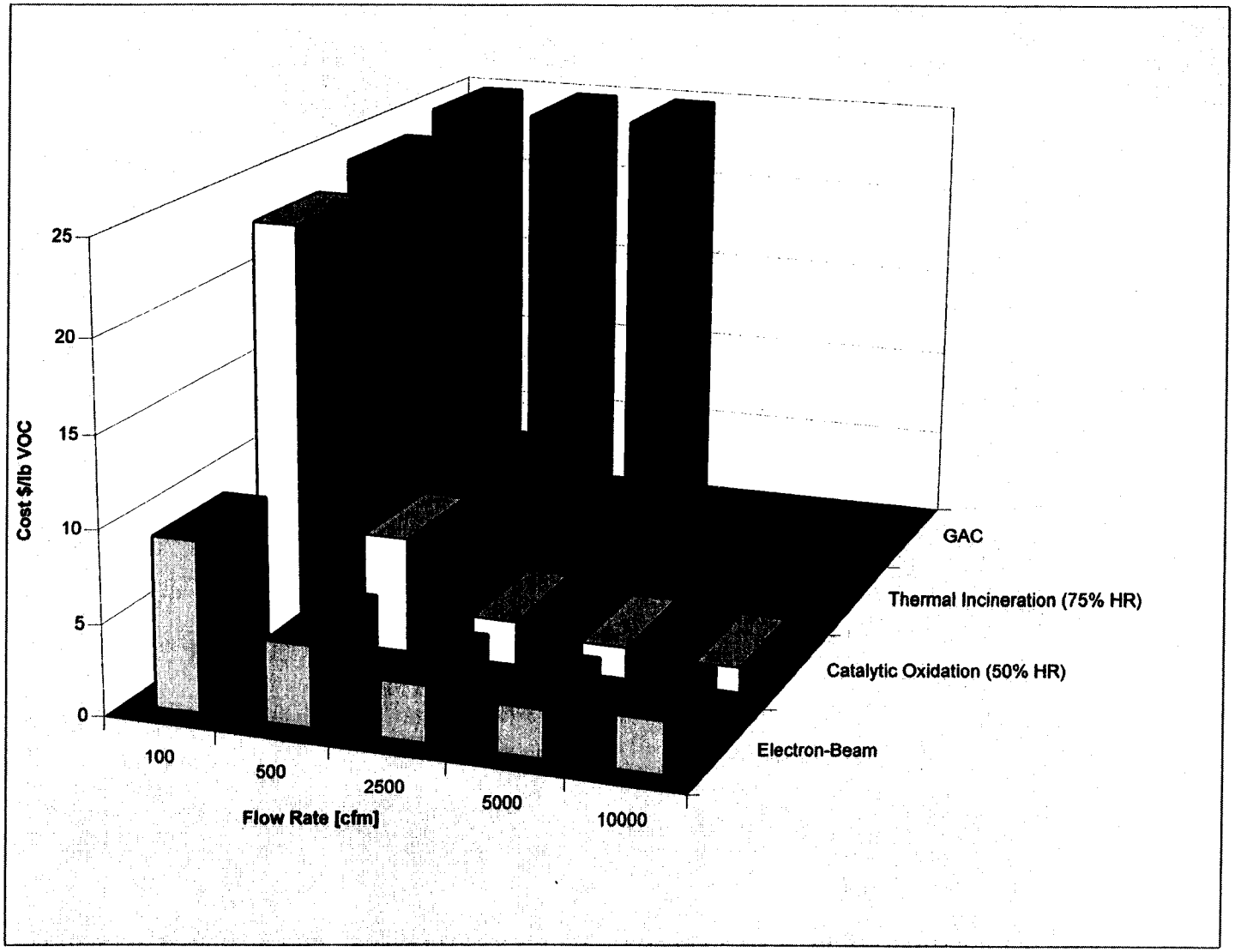
A5. Cost Estimate for Destruction of 25 ppm CCl_4



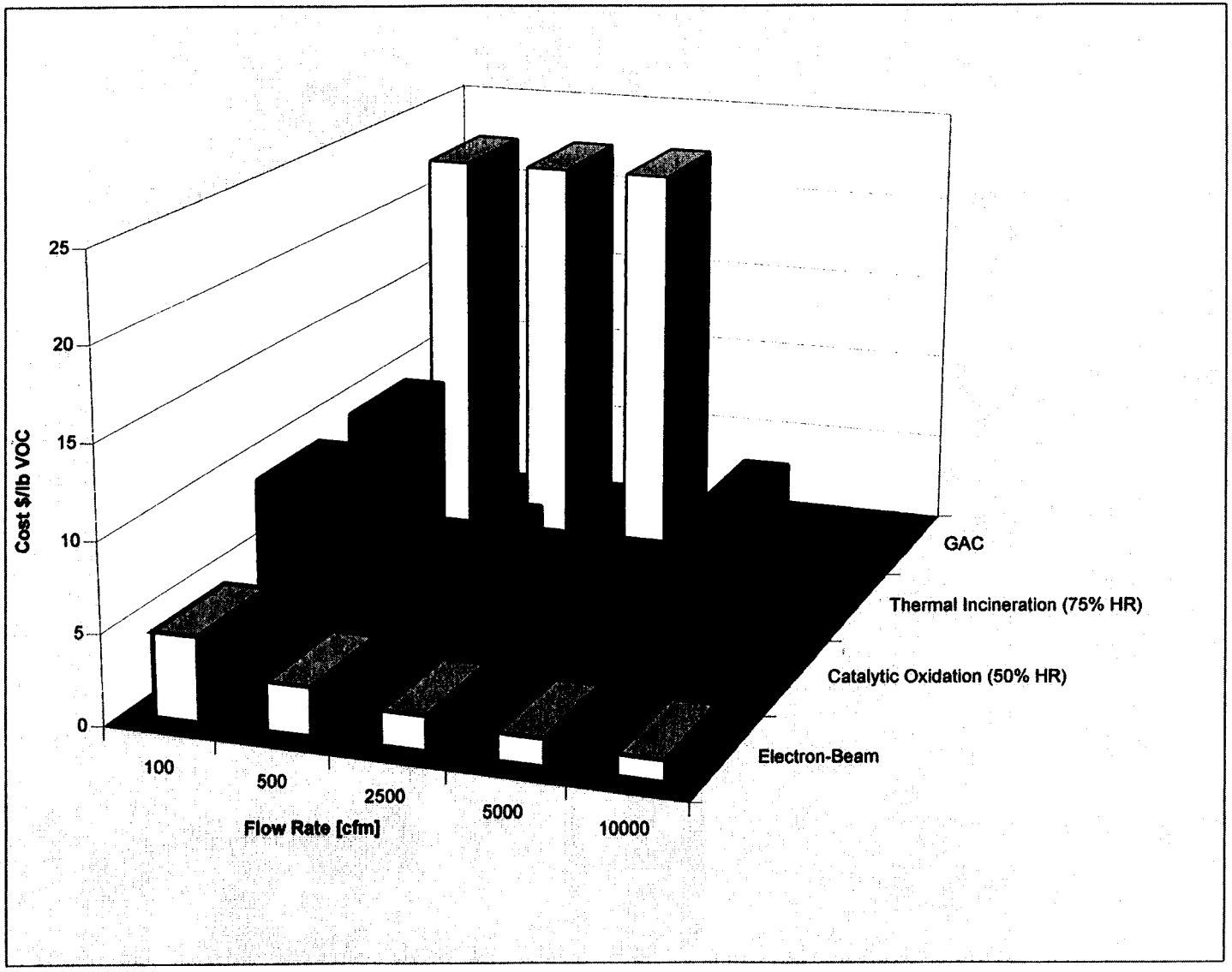
A6. Cost Estimate for Destruction of 50 ppm CCl4



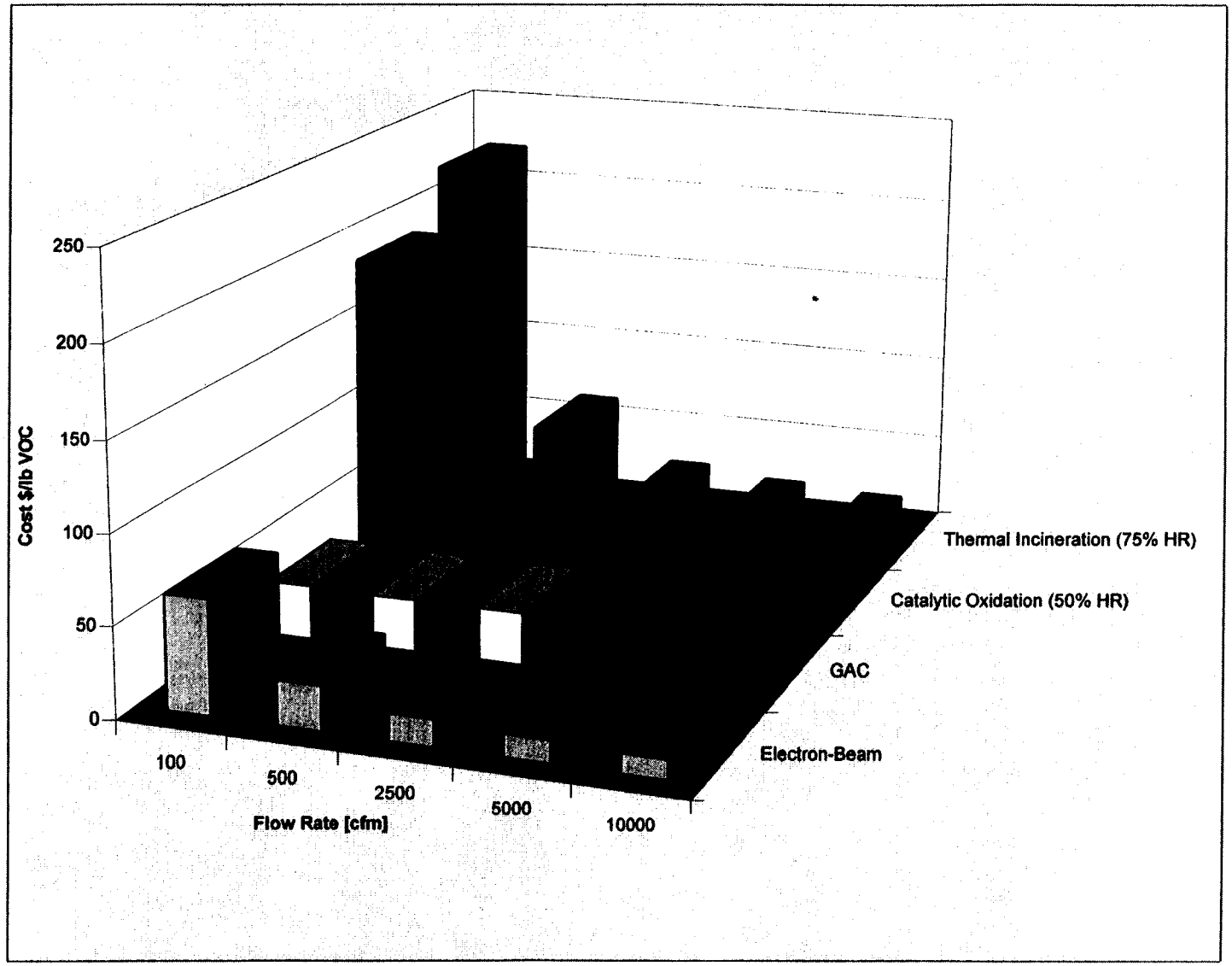
A7. Cost Estimate for Destruction of 200 ppm CCl_4



A8. Cost Estimate for Destruction of 500 ppm CCl_4

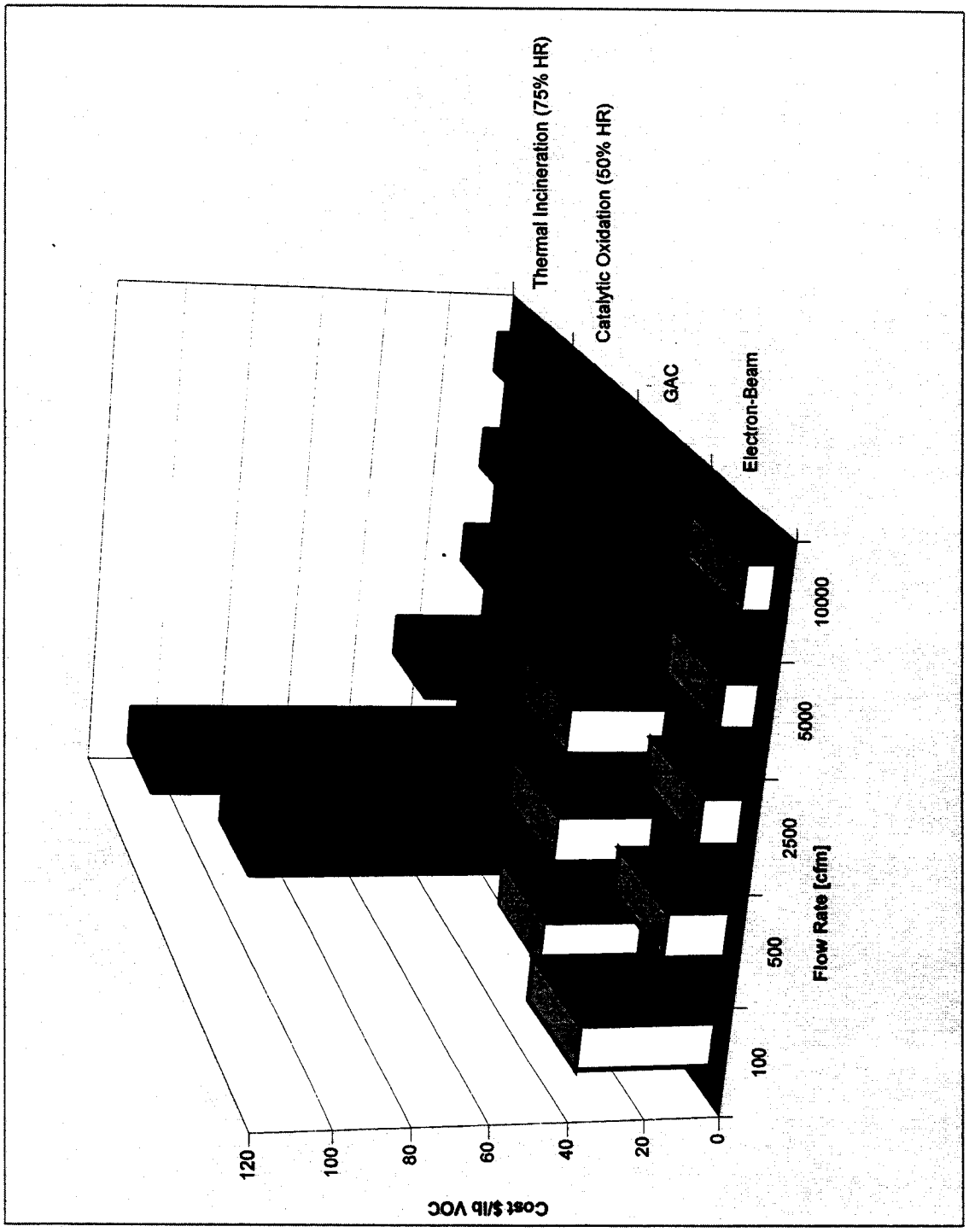


A9. Cost Estimate for Destruction of 25 ppm TCA

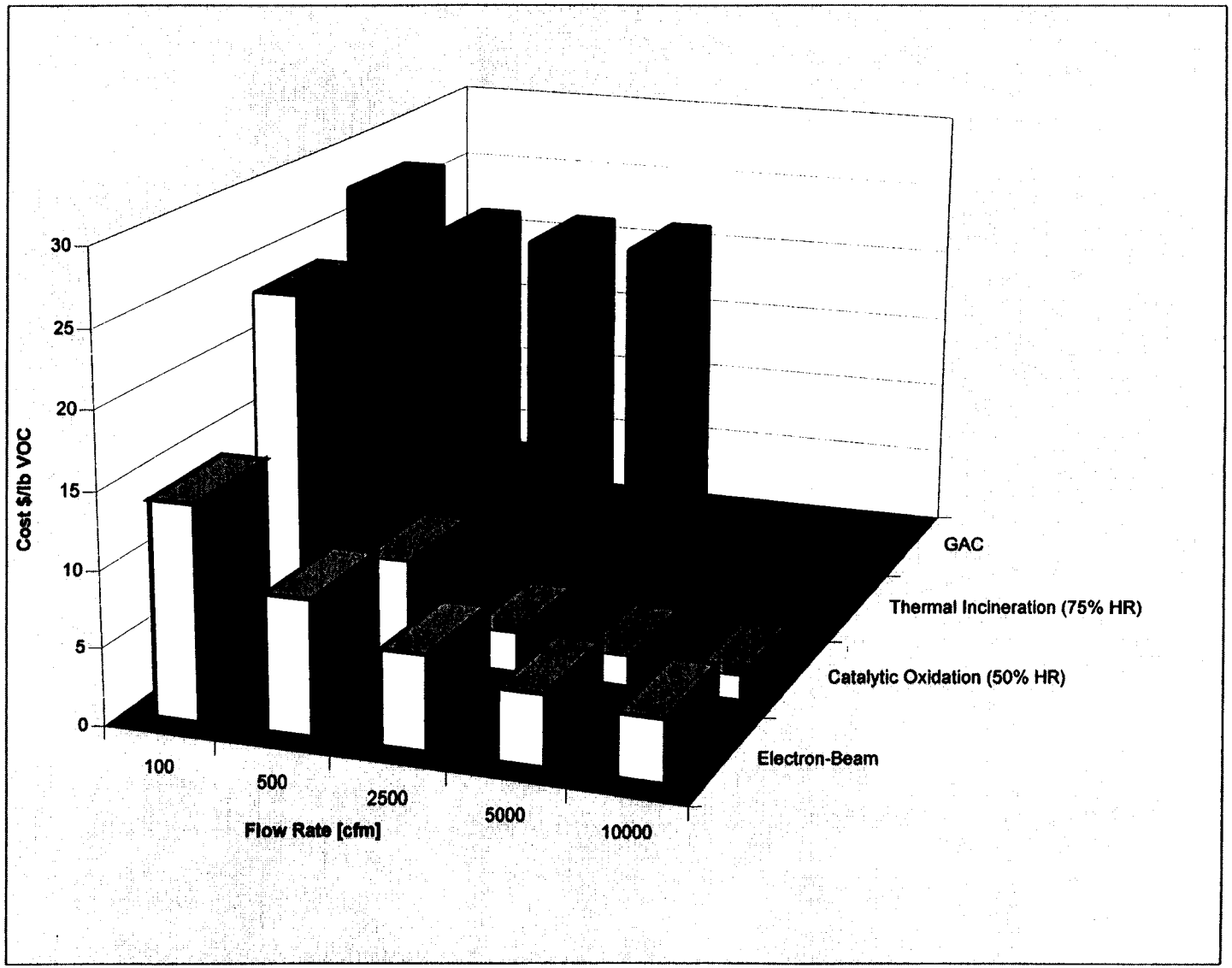


Compare Chart 35

A10. Cost Estimate for Destruction of 50 ppm TCA



A11. Cost Estimate for Destruction of 200 ppm TCA



A12. Cost Estimate for Destruction of 500 ppm TCA